# Tweel™ Technology Tires for Wheelchairs and Instrumentation for Measuring Everyday Wheeled Mobility

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# Tweel™ Technology Tires for Wheelchairs and Instrumentation for Measuring Everyday Wheeled Mobility

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# SUMMARY


Advances over the last few decades have dramatically improved the quality of life for wheelchair users, from accessibility to overall ride comfort. However, important aspects of wheelchair usage remain poorly understood. Increased knowledge about wheelchair usage could help improve comfort and prevent secondary disabilities resulting from long term use of wheelchairs. Furthermore wheelchair usage information would help design products according to user needs.

This thesis is focused on two aspects related to wheeled mobility: 1) Evaluating the impact of a new tire design on powered mobility, and 2) Instrumentation that permits better monitoring and assessment of wheeled mobility in everyday use.

Extensive studies have been conducted in the past that show the benefits of using a pneumatic tire over solid foam core tires. Benefits include lower rolling resistance and a more comfortable ride. However, pneumatic tires have a shorter lifespan and require maintenance. The Tweel™ technology tires developed by Michelin USA are comprised of an outer polyurethane ring supported by polyurethane fins instead of metal spokes, which allow the tire to deflect under pressure. As a wheelchair tire they offer a potential breakthrough as they have deflection properties similar to a pneumatic tire while maintaining the low maintenance of a solid foam-core tire. A study was conducted to compare the Tweel™ technology tires to standard solid foam-core tires for vibration transmission, traction and overall life span.

A wheelchair instrumented with accelerometers was used to record the vibration transmitted to the user. Tests were conducted over five different surfaces and 3 sets of

obstacles commonly traversed in everyday mobility. Additionally, traction testing was conducted by driving the wheelchair along a banked turn, whose angle of inclination increased with distance, until the wheelchair started slipping. Lastly, a month long field trial was conducted with ten wheelchair users to get user feedback on the Tweel™ technology tires and to test durability in everyday mobility.

Improved ride comfort with low maintenance was considered the major selling point for Tweel™ technology tires before tests were conducted. However, the Tweel™ technology tires failed produce any significant difference in accelerations measured at the wheelchair seat when compared to solid foam-core tires. Additionally, the expected life span for a wheelchair tire is 12-18 months, while the Tweel™ technology tires showed significant signs of deterioration after a month long field trial, thus indicating a short life span. On the other hand, the Tweel™ technology tires provided better traction on both dry and wet concrete. Overall the Tweel™ technology tires have to be re-engineered to provide better damping properties, leading to lower vibrational levels transmitted to the user. Furthermore, the tire's life span has to be improved significantly before these tires become a viable option.

A striking result that was derived from this study was the level of health risk posed to a wheelchair user from whole-body vibration exposure during everyday mobility. It showed that the vibration levels for an average user was within the caution zone set by the ISO standard 2631-1, which means that there is an elevated risk of health impairment from prolonged exposure. Additionally, in terms of perceived comfort, the level is above the 'Uncomfortable' range for most surfaces, suggesting work needs to be done to improve the overall ride comfort of the users and prevent detrimental effects from long term use.

Although a lot of useful information was gathered from tests within the simulated environments, it was difficult to relate the data to everyday mobility. This is due to a lack of information available on actual wheelchair usage consisting of average time of use, speed to travel and percentage of time spent indoors and outdoors. Therefore, the second section this thesis addressed the need to develop a methodology of measuring mobility in everyday usage. This section is part of a greater ongoing research project at CATEA (Center for Assistive Technology and Environmental Access) aimed at understanding everyday wheelchair usage. Methodology was developed to measure bouts of mobility that characterize wheelchair usage; which includes the number of starts, stops, turns and distance traveled through the day.

Three different technologies which included, Accelerometer unit on the rim of the drive wheel, Gyro-Accelerometer unit on the frame of the chair and Reed switches, were tested. Testing included various criteria for accuracy, durability and compatibility for measuring bouts of everyday wheeled mobility. Tests were conducted on both indoor and outdoor environments to check if the sensors effectively picked up various aspects of everyday mobility under different conditions. As a final test, sensors were attached to two power wheelchairs to monitor bouts of mobility throughout a day. The objective of this test was to process real-world data and check for unexpected results.

Although a single technology could not be used to measure all aspects of mobility, the Accelerometer unit on the rim met the design criteria for measuring starts stops and distance, while the Gyro-Accelerometer unit met the requirements for measuring turns. Moreover, the accuracy level of the sensors was well over 90% in measuring starts, stops, distance and turns. However, some work needs to be done to improve the battery life and compatibility of the units.

# CHAPTER 1

# INTRODUCTION

Advances over the last few decades have dramatically improved the quality of life for wheelchair users, from accessibility to overall ride comfort. However, important aspects of wheelchair usage remain poorly understood. Increased knowledge about wheelchair usage could further improve comfort and prevent any secondary disabilities resulting from long term use of wheelchairs. Furthermore, wheelchair usage information would help design products according to the needs of the user.

This thesis is focused on two aspects related to wheeled mobility: 1) Evaluating the impact of a new tire design on powered mobility, and 2) Instrumentation that permits better monitoring and assessment of wheeled mobility in everyday use.

## 1.1 Identifying Need

Focus group studies consisting of manual and power wheelchair users were conducted to determine the problems users experience with their wheelchairs with a focus towards tires. Overall, the users were pleased with their tires but reported several weaknesses. The users complained about rough ride on uneven surfaces like bricks and uneven/broken sidewalks. They also cited poor traction on inclined surfaces under wet and dry conditions, and often mentioned maintenance as a key issue including cleaning on a regular basis, occasional repair or replacement of parts. Users expressed desire for tires that were low maintenance and had a life span of 5-7 years.

Michelin Americas designed a new tire based upon Tweel™ technology that was aimed at addressing some of these needs. The new tire design aimed at improving ride comfort and providing better traction. Michelin contacted Georgia Tech and requested testing of Tweel™ Technology tires to determine feasibility within the wheelchair market. Prototype testing consisted of monitoring wheelchair movements in simulated environments to assess performance of Tweel™ Technology tires compared to solid-foam core tires and the verify if the Tweel™ Technology tires met its design objectives.

Although a lot useful information was gathered from tests within simulated environments, it was difficult to relate the data to everyday wheelchair mobility. That is due to a lack of information available on actual wheelchair usage consisting of average time of use, speed of travel and percentage of time spent indoors and outdoors. Therefore, this thesis addresses the need to develop a methodology of measuring mobility in everyday usage. The data gathered from everyday usage would help in gaining a better insight on the application of simulated results.

### 1.2 Tweel™ Technology Tires

The Tweel™ technology tires, which are shown in Figure 1, consist of a metal hub, polyurethane fins and outer ring. Some versions also have a rubber tread (for drive wheel only). The design allows the tires to deflect under pressure similar to pneumatic tires. Since the tires are entirely solid, they do not require regular maintenance like pneumatic tires. Testing at Georgia Tech was limited to power wheelchairs due to design and manufacturing constraints at Michelin.


**Figure 1: Tweel™ drive wheel and caster installed on a wheelchair**

Extensive studies have been conducted in the past that show the benefits of using a pneumatic tire over solid foam core tires, especially in manual wheelchairs. Benefits include lower rolling resistance and a more comfortable ride (1-3). However, pneumatic tires have a shorter lifespan and require maintenance. The Tweel™ technology tires tested in this study were designed to have properties of a pneumatic tire while preserving the low maintenance of a solid core tire. An engineering case study was developed to compare the performance of Tweel™ technology tires to that of standard foam core tires used on power wheelchairs. Performance was compared using three constricts: 1) The health effects and perceived comfort level resulting from the vibration transmitted to the wheelchair; 2) Traction provided by the tires under wet and dry conditions; 3) The overall life span of the tires.

### 1.2.1 Vibration Exposure

Vibration exposure can have adverse effects on a person depending on the duration and magnitude of exposure. Standards have been developed that set the limit of exposure for a seated person. International Standard Organization (ISO) (4) and the Society of Automotive Engineers (SAE) (5) prescribe similar methods for instrumentation and data analysis to calculate the vibration exposure effects on the user. Both standards measure acceleration at the contact surface between the buttocks and seat surface.

ISO 2631-1 is the most accepted standard for vehicle vibration studies and establishes limits for safety and comfort. The *exposure caution zone* is based upon the time of exposure and weighted magnitude of acceleration; it reflects the maximum allowable limit for human safety. Furthermore, the ISO Standard specifies the location and orientation for the accelerometer, as well as different data analysis methods that can be used.

A few studies have been conducted to apply ISO 2631 to wheelchairs. An early study by Thacker and Foraiati (6) measured accelerations while traveling over 6 mm and 16 mm rods at different speeds. They found accelerations were directly related to speed and a 4-hr 'comfort' limit was exceeded in certain situations while others had a 16 hr comfort limit. VanSickle et al. (7) measured the forces acting on a manual wheelchair while conducting the ANSI/RESNA standards double drum and curb drop tests and compared them to loads measured from a simulated road course consisting of eight obstacles and barriers; 2.5, 5.1 and 7.7 cm bumps, truncated dome strip, carpet, 1.6 cm door threshold, ramp, 5 cm curb drop, and a rumble strip. The forces measured during the curb drop test and double drum test were an order of magnitude higher compared to the simulated road course. VanSickle et al. (8) also measured acceleration transmitted to a manual wheelchair user during a simulated road course along with a 4-hr field trail to determine how well the standards apply to wheelchair users during community mobility. Simulated road course accelerations exceeded the 8-hr exposure limit defined by ISO 2631-1(4). The authors postulated that the methodology as set by ISO 2631-1 might not validly estimate the risk of exposure on wheelchair users. The ISO standard assumes that the exposure is near-constant for the time frame of the test, while wheelchair users are exposed to infrequent, but large impulsive accelerations throughout the day.

DiGiovine et al. (9) compared acceleration damping offered by different wheelchair cushions and backrests mounted on a manual wheelchair. The participants were asked to traverse over nine environmental barriers; 2.5, 5.1, 7.7 cm sinusoidal bumps, ramp, 5 cm curb drop, carpeting, dimple strips, 1.6 cm door threshold, and a rumble strip. Two accelerometers were used to measure vertical and fore-aft accelerations; one was placed on the wheelchair seat and other one on a bite-bar to measure accelerations of the subject's head. The sinusoidal bumps and the curb drop produced the highest accelerations. Most barriers did not result in different accelerations across cushions or backrests, and only a few isolated differences were identified. Wolf et al. (10) conducted a study on different paved surfaces and showed how different brick patterns affect the vibration exposure on wheelchair user. The users traversed over six different sidewalk surfaces approximately 1.2 m wide and 7.6 m long at two different speeds (1 m/s, 2 m/s) in power wheelchairs and a single speed of 1m/s for manual wheelchairs. The ISO limit for an 8-hour exposure was exceeded for all surfaces at high speed of 2m/s.

The objective of the study presented in this thesis was to analyze the difference in ride accelerations and comfort between Tweel™ technology tires and standard solid core tires used in power wheelchairs. Testing included driving an instrumented power wheelchair over several different surfaces and sets of obstacles with three specific aims: 1) to determine the vibration exposure levels experienced by the user on common surfaces are traversed in everyday use, 2) to determine vibration exposure levels from different potholes and risers, and 3) to calculate the average time a user would have to travel on each of the surfaces to approximate the vibration exposure limits. In order to validate the results from the instrumented testing, a subjective test was also conducted with the help of trained Michelin test drivers.

### 1.2.2 Traction

As mentioned earlier, focus groups were conducted at the beginning of this study to gauge interest in the Tweel™ technology tires and to better understand concerns about current tire options. One concern was tire traction, especially under wet conditions and while traversing an inclined surface. A test was developed to compare the level of grip offered by the Tweel™ technology tires under both wet and dry conditions in comparison to the standard foam core tires. This test consisted of driving a wheelchair along a banked turn, whose angle of inclination increased with distance. The test was stopped once the wheelchair lost traction and slipped downwards.

### 1.2.3 Durability

Durability and low maintenance has been a high concern for wheelchair users and is the primary reason pneumatic tires are not used even though they might be beneficial in other areas. Based upon user focus groups and surveys, the average life span of the current solid foam core tires is between 12-18 months. Therefore it was important that the Tweel™ technology tires last a comparable time frame.

A field study was conducted, wherein nine power wheelchairs were fit with Tweel™ casters and/or drive wheels for a month-long trial. One additional subject used the Tweel™ tires for 3 months. A total of 22 casters and 10 drive wheels were evaluated. The Tweel™ technology tires were developed to operate under 10% deflection level. Therefore, the force required to deflect these tires by 5% and 10% was measured before and after the field trial to check for any deterioration in material properties. The tires were also inspected for visual damages after the field study.

## 1.3 Wheelchair Usage

Studies have shown that wheelchair users, especially manual wheelchair users develop secondary disabilities from long term usage. Besides injuries suffered due to exposure from vibration as discussed earlier, manual wheelchair users face the risk of repetitive strain injuries from long term use. Gaal et al. (11) conducted a study of 109 users who had experienced incidents and suffered injuries as a result. These incidents included “Tips and Falls”, “Component Failures” and “Other” events. The study was aimed at better understanding the reason behind the incidents and to help users make more informed decisions when choosing a wheelchair. It also discussed future design improvements that could help reduce the number of incidents.

A more striking study conducted by Cooper et al. (12), surveyed manual wheelchair users to determine the prevalence of repetitive strain injury after long term use. The surveys showed that 20% of users reported upper extremity pain 5 years post-injury while 46% of the users reported pain after 15-19 years post-injury. While the percentage of wheelchair users suffering from carpal tunnel syndrome (CTS) was between 49-73%. The authors postulated that the pain was related to overuse of the arm during transfers and wheelchair propulsion.

Furthermore, studies have been conducted to understand the biomechanics of wheelchair use to gain an insight on the process that might cause the injuries. However, one limitation of analyzing data gathered in simulated environments is the lack of available data on actual wheelchair usage upon which to compare. Moreover, Mattison et al. (13) showed that simulated environments like treadmills are not are a good way of measuring propulsion effort and usage for manual wheelchairs, since everyday mobility involves moving in short burst around furniture and other obstacles. A combination of lack of data availability and inexactness of relating data from simulated use to everyday use makes it is hard to determine the actual conditions experienced during everyday mobility.

A few studies have been conducted recently on wheelchair users, measuring the distance and time of travel in a day. Cooper et al. (14) conducted a study on the driving characteristics of powered wheelchair users. The study contained 17 power wheelchair users studied over a 5 day period; it reported the average distance traveled by the group, as well as the speed at which they traveled. Similar studies were also conducted by Sonenblum et al. (15) and Fitzgerald et al. (16) comprising of power and manual wheelchair users respectively. These studies reported the average distance traveled in a day along with average speed. Although these papers report useful information about wheelchair mobility, added information would increase the effectiveness of correlations between simulated results and wheelchair usage.

One area of improvement would be to measure bouts of mobility that characterize wheelchair usage. It is believed that the most effort placed on the users arms are during starts, stops and turns as they require the most effort since the user has to overcome inertia forces. Therefore, this thesis aims at developing a methodology to measure the number of starts, stop and turns a user performs everyday along with the distance traveled. This methodology could be expanded in the future to measure the vibration transmitted to the user from the wheelchair to determine possible health effects and perceived level of comfort.

## 1.4 Thesis Structure

The first part of this thesis covers the study conducted for Michelin Americas for their Tweel™ technology tires. This part is an extensive engineering case study developed to compare the performance of the Tweel™ technology tires to the current options available in the market. Chapter 2 describes the testing conducted at the Laurens Proving Ground operated by Michelin, where the Tweel™ technology tires were compared to the standard solid foam-core tires for Vibration Transmission and Traction. Chapter 3 covers durability testing done during a month long field trial. This included checking for visible damage and measuring force-deflection responses before and after the field trial.

The second section of this thesis is part of a greater ongoing research project at CATEA (Center for Assistive Technology and Environmental Access) aimed at understanding everyday wheelchair usage. The aim of this portion of the thesis was to develop a methodology to measure bouts of mobility that characterize wheelchair usage. This requires the measurement of the number of starts, stops, turns and distance traveled through the day. The data gathered from this study would also help relate the data gathered in the Michelin study to everyday usage. The methodologies tested along with results are discussed in Chapter 4.

# CHAPTER 2

# SIMULATED ROAD COURSE

Tests were formulated in order to evaluate the performance of Tweel™ technology tires and compare them to the standard foam-core tires. The tests evaluated the vibration transmitted from the tires to the frame of the wheelchair and the level of grip provided by the tires. Vibration transmission was tested since the Tweel™ technology tires have deflection properties similar to a pneumatic tire, thus it was expected that they would dampen out the vibration transmitted to the wheelchair, improving ride comfort. Furthermore, the rubber tread on the drive wheels was designed to provide better traction than standard solid foam-core tires; consequently, traction testing was conducted on the tires. All tests were preformed at the Lauren's Proving Grounds, operated by Michelin Americas.

## 2.1 Vibration transmission

Testing followed the ISO 2631-1 standard for evaluation of human exposure to whole-body vibration (4). ISO 2631-1 is the most accepted standard for vehicle vibration studies and establishes limits for safety, fatigue and comfort. As discussed earlier, ISO 2631-1 has been used in the past to study the vibrational effects on a wheelchair user.

### 2.1.1 Instrumentation

A tri-axial accelerometer (PCB 356B08) was mounted beneath the seat of the wheelchair with a magnet as shown in Figure 2. The accelerometer was positioned such that it was approximately underneath the ischial tuberosities of the seated person. Mounting the accelerometer on the rigid wheelchair seat permitted study of vibration independent of the cushion and was consistent with previous works on wheelchair vibration (17, 18). The axes of the accelerometer were aligned with the axes of the motion of the wheelchair according to the ISO standard. Z-axis was aligned with the vertical, Y-axis toward the left and the X-axis was aligned with the forward direction of the wheelchair.

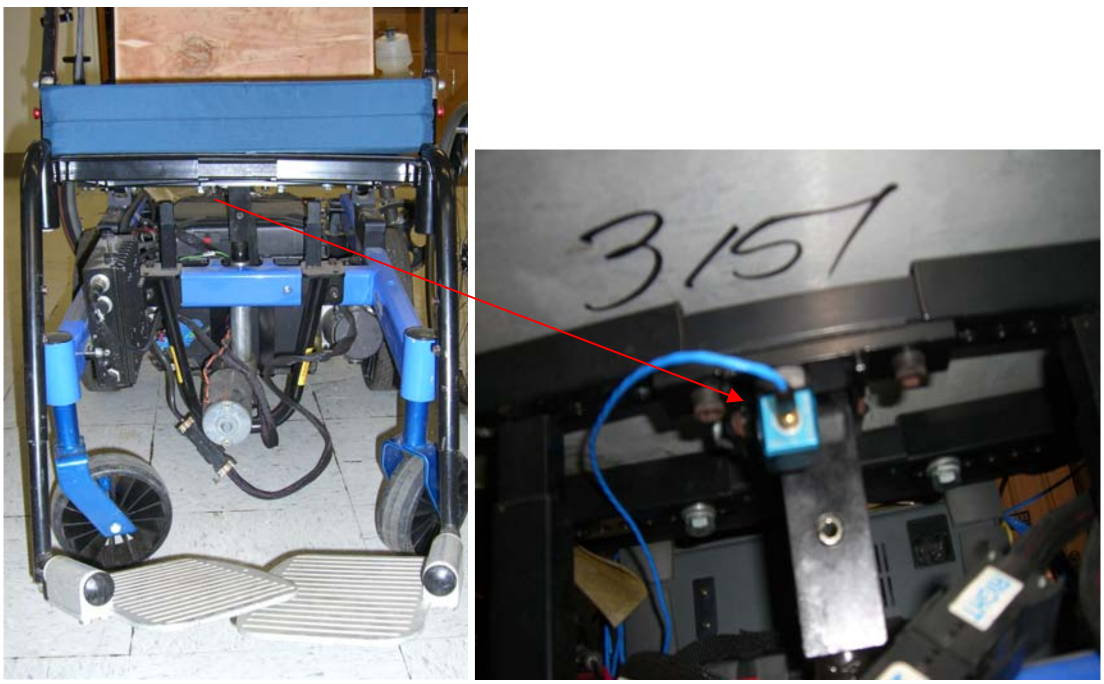


**Figure 2: Accelerometer mounting**

The accelerometer compensated for gravity within its internal electronics, therefore simplifying data analysis. Magnet attachment afforded convenience and was consistent with Michelin procedures. The available frequency range due to mounting the accelerometer using a magnet was <10000 Hz. The accelerometer was also lightweight, had high sensitivity and low drift making it ideal for this application. Accelerometer drift was an at least order of magnitude lower than the lowest recorded acceleration values; therefore, it was ignored in the analysis.

An OROS (OR2516) DAC system was used in conjunction with the accelerometer and readings were sampled at 1024 Hz. Each individual axis was recorded on a separate channel in the DAC system.

### 2.1.2 Test Methods

#### *2.1.2.1 Surfaces*

Five different surfaces were selected to represent those common to everyday outdoor mobility: two types of concrete (rough and smooth), asphalt, grass and gravel (Shown in Appendix A). The wheelchair was driven four times over each of the surfaces at two different speeds for a distance of 20m. The tests were then repeated with Tweel™ drive wheels and casters resulting in a total of 80 test runs over the different surfaces.

Surfaces were traversed at 1 m/s and 1.5 m/s. Prior to the test, speed on the controller of the wheelchair was set using a GPS system, (Race logic Vbox III) which has a resolution as low as 1 cm and measures speed to the nearest 0.045 m/s. Due to power limitations, the GPS readings were not recorded during testing, however the speed was verified with a stop watch. The run was considered acceptable if the wheelchair traveled the 20 m distance within 0.2 seconds of the desired time. These two wheelchair speeds bracket the average walking speed of 1.2 m/s (19). Power wheelchairs are designed to travel at speed greater than 2m/s with some configured to exceed 3m/s. Therefore, in everyday mobility, some power wheelchair users will travel at speeds that greatly exceed walking speed, but speeds are often reduced while traversing rough surfaces.

#### *2.1.2.2 Obstacles*

Two different test tracks were configured to mimic different types of obstacles that a wheelchair user might experience in daily mobility. The first course consisted of a 2.3 cm flat edge riser in the concrete followed by 3 wooden strips with 0.64 cm, 1.27 cm, and 2.54 cm heights followed by another 2 cm riser. The heights of the wooden strips were selected in accordance to the Americans with Disabilities Act (ADA) (20), which states that any obstacle over 0.64 cm have a tapered edge. The 0.64 cm strip had a flat edge, while the edges of the 1.27 cm and 2.54 cm strips were tapered by approximately 30 degrees.

Tests were repeated on the same track but in the reverse direction resulting in the step-up obstacles (risers) becoming step-down obstacles. For the 3$^{rd}$ test run, the wheelchair was driven over a 35 m strip of concrete with several different types of potholes ranging from 0.76 cm - 5 cm in depth and 5 cm – 61 cm in length; a side view of the pothole course is shown in Figure 3. The obstacles on both tracks were at least 91 cm wide (into the plane shown in Figure 3), which ensured that all of the wheels traversed over them.

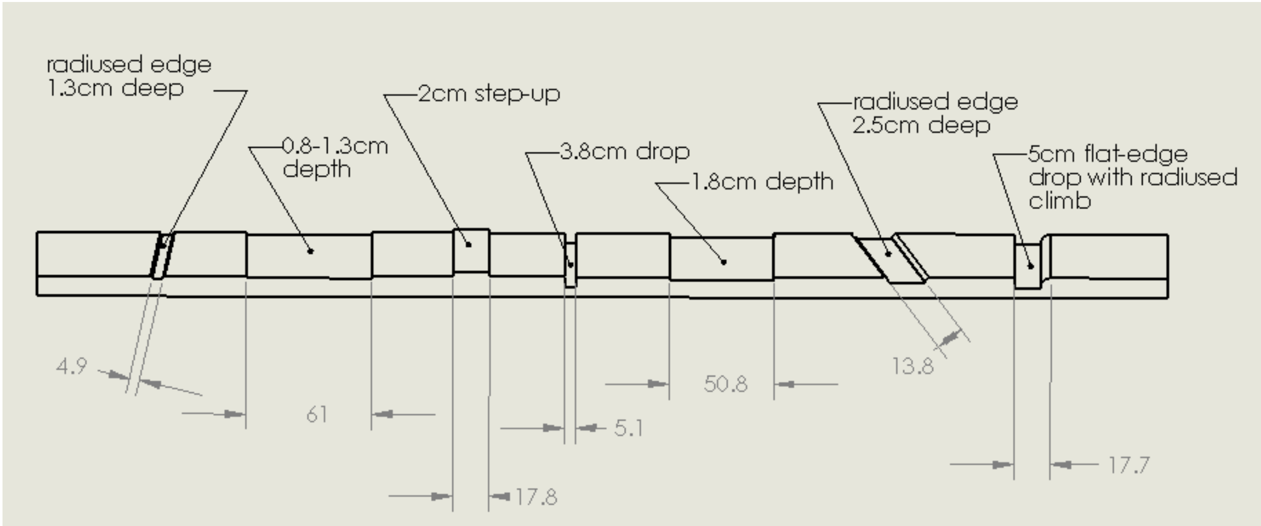



**Figure 3: Obstacle course with potholes;**

**Note: The distance between obstacles has been scaled down by a factor of 10 and all dimensions are in centimeters**

Testing over obstacles was conducted at only 1 m/s to permit stable control of the wheelchair. Each set of tests was repeated 4 times. A run was considered valid if the test duration recorded using a stopwatch, was within 0.5 s of the calculated time reflecting the length of the test run.

### 2.1.3 Data Analysis

The data was analyzed in accordance with the ISO 2631-1 standard for evaluation of vibration. Health-caution zones are defined using the frequency weighted RMS root mean square) acceleration method. A script was written in Matlab (Appendix B) which processed the raw data through a combination of 4 filters as prescribed by the ISO standard. First two were Butterworth high pass and low pass filters, combining to form a band-pass filter given by:

$$|H_h(p)| = \left| \frac{1}{1+\sqrt{2}\omega_1 / p + (\omega_1 / p)^2} \right| \qquad (1)$$

$$|H_l(p)| = \left| \frac{1}{1+\sqrt{2}p / \omega_2 + (p / \omega_2)^2} \right| \qquad (2)$$

Where,

$H_h$ = High pass filter

$H_l$ = Low pass filter

p = Laplace domain variable

$\omega_1 = 2\pi f_1$

$f_1$ = Corner frequency (intersection of asymptotes) = 0.4 Hz

$\omega_2 = 2\pi f_2$

$f_2$ = Corner frequency = 100 Hz

Two additional filters were used to weight the amplitude at different frequencies in accordance to the effect they have on the human body in the vertical direction. Only one additional filter was used for the weighting the vibrations in the horizontal plane.

$$|H_t(p)| = \left| \frac{1+p/\omega_3}{1+p/Q_4\omega_4 + (p/\omega_4)^2} \right| \qquad (3)$$

Where,

$H_t$ = Acceleration-velocity transition filter

$\omega_3 = 2\pi f_3$

$\omega_4 = 2\pi f_4$

$Q_4$ =0.63

$f_3 = f_4 = 12.5$ Hz (For Vertical motion)

$f_3 = f_4 = 2$ Hz (For lateral motions)

$$\left|H_s(p)\right| = \left|\frac{1 + p/Q_5\omega_5 + (p/\omega_5)^2}{1 + p/Q_6\omega_6 + (p/\omega_6)^2} \cdot \left(\frac{\omega_5}{\omega_6}\right)^2\right| \quad (4)$$

Where,

$H_s$ = Upward step filter

$Q_5 = Q_6 = 0.91$

$f_5 = 2.37$ Hz

$f_6 = 3.35$ Hz

These filters are referred to as the acceleration-velocity transition (Equation 3) and upward step (Equation 4). The first filter can be considered as being proportional to acceleration at lower frequencies and velocity at higher frequencies. The second filter takes into account the steepness of the slope; proportional to jerk. The upward step filter was only used for data in the vertical (Z) direction.

After the raw data was processed through the filters it was converted to the frequency domain using a Fast Fourier Transform (FFT). The power spectral density of individual 1/3 octaves was calculated by integrating the area under the curve. The center value of the 1/3 octaves were calculated recursively using the ISO standard formula:

$$f_2 = \left(2^{\frac{1}{3}}\right) \times f_1 \quad (5)$$

$f_1$ = 1 Hz for first value

The cumulative power spectral density (PSD) for each of the axis was calculated using:

$$a_w = \left[ \frac{1}{n} \sum_i^n (a_{wi})^2 \right]^{\frac{1}{2}} \qquad (6)$$

$a_w$ = Frequency-weighted RMS acceleration

$a_{wi}$ = Weighted RMS acceleration for the ith one-third octave band

n = Number of one-third octaves

The last center frequency for the 1/3 octave was set at 80 Hz as prescribed by the ISO standard. This cutoff frequency completely covers the maximum frequency typically experienced in vehicular dynamics (approximately 50 HZ) (21, 22).

The ISO standard recommends that the assessment of the effect of vibration on health should be made with respect to the highest frequency-weighted acceleration determined in any axis of the seat pan. In this case the vibration from the Z-axis was significantly larger than the other axes on all surfaces except for smooth and rough concrete. Therefore, in order to be consistent between surfaces and to relate to previously published data (18), Z-axis acceleration was used for all the runs.

Perceived comfort levels were calculated by combining the acceleration RMS from the individual orthogonal axes:

$$a_v = \left( k_x^{\,2} a^2{}_{wx} + k_y^{\,2} a^2{}_{wy} + k_z^{\,2} a^2{}_{wz} \right)^{\frac{1}{2}} \qquad (7)$$

where, $k_x$=$k_y$=$k_z$=1 (For comfort)

The resulting total weighted RMS acceleration was compared to comfort levels prescribed by ISO 2631-1.

Multiple sets of vibration can be added according to:

$$a_{w,e} = \left[ \frac{\sum a^2{}_{wi} \cdot T_i}{\sum T_i} \right]^{\frac{1}{2}} \qquad (8)$$

Where,

$a_{w,e}$ = Equivalent vibration magnitude (RMS. acceleration in $m/s^2$);

$a_{wi}$ = Vibration magnitude (RMS acceleration in $m/s^2$) for exposure duration $T_i$

Equation 8 calculates the energy-equivalent vibration magnitude corresponding to the total duration of exposure.

The results from the combined PSD values were used to determine if the tires differed with respect to rider comfort or health effects. For surface data analysis, a three-way ANOVA (analysis of variance) was used to tests the effects of tire type, speed and surface. For the obstacle analysis, a two-way ANOVA was used to test the effects of tire type and obstacle. Post-hoc pairwise comparisons were made using Tukey's test. P-values for all tests are reported with results being discussed for values of $p<0.1$. In statistical hypothesis testing, the p-value is the probability of obtaining a result at least as extreme as a given data point, assuming the data point was the result of chance alone. Significane level of 0.1 was chosen since the data set is not sufficiently large.

### 2.1.4 Results

The average RMS value for both tires over different surfaces and obstacles with respect to health effects and perceived comfort are included in Table 1 and Table 2 while, Table 3 contains the results from the ANOVA testing. No significant differences were found across tire type in the surface analysis ($p>0.916$), suggesting the Tweel™ technology tires and standard tires performed in a similar manner. Similar results were seen for the obstacle analysis ($p>0.105$) for comfort; no significant difference could be seen in terms of comfort. However, a significant difference in health effects for obstacles ($p=0.23$); the Tweel technology tires showed higher RMS values. Analysis of the surface type and speed factors produced significant differences for both health and comfort RMS variables. The obstacle analysis produced significant effects for obstacle type ($p<0.015$) and the interaction between obstacle and tire type was significant ($p=0.000$) for both health and comfort RMS values. The complete set of data is included in Appendix C, while the ANOVA analyses are posted in Appendix D and E for surfaces and obstacles, respectively. The surface/ obstacle number used in the ANOVA analysis correspond to the numbers in Table 1 and Table 2 following the surface/obstacle names.

**Table 1: Average RMS Values for health effects**

| | **Standard tire** | | **Tweel™** | |
|---|---|---|---|---|
| **Surfaces & Obstacles** | **1m/s** | **1.5m/s** | **1m/s** | **1.5m/s** |
| Asphalt (1) | 2.006 | 2.508 | 2.401 | 2.535 |
| Rough Concrete (2) | 0.489 | 0.787 | 0.637 | 0.767 |
| Smooth Concrete (3) | 0.405 | 0.681 | 0.505 | 0.641 |
| Grass (4) | 2.102 | 3.073 | 1.768 | 2.848 |
| Gravel (5) | 4.747 | 6.673 | 4.885 | 6.445 |
| Obstacles run with riser (6) | 3.591 | | 3.720 | |
| Obstacles run with step-down (7) | 3.627 | | 3.878 | |
| Obstacle run with potholes (8) | 4.205 | | 4.131 | |

**Table 2: Average RMS values for perceived comfort**

| | Standard tire | | Tweel™ | |
|---|---|---|---|---|
| **Surface & Obstacles** | **1m/s** | **1.5m/s** | **1m/s** | **1.5m/s** |
| Asphalt (1) | 2.144 | 2.754 | 2.566 | 2.842 |
| Rough Concrete (2) | 0.717 | 1.353 | 0.897 | 1.183 |
| Smooth Concrete (3) | 0.673 | 1.417 | 0.879 | 1.466 |
| Grass (4) | 2.544 | 3.618 | 2.265 | 3.272 |
| Gravel (5) | 5.016 | 6.936 | 5.166 | 6.714 |
| Obstacles run with riser (6) | 3.996 | | 4.110 | |
| Obstacles run with step-down (7) | 3.917 | | 4.172 | |
| Obstacle run with potholes (8) | 4.752 | | 4.562 | |

**Table 3: Results of surface and obstacle ANOVA analysis (p values)**

| 3-way ANOVA for *surface* data | Health | Comfort |
|---|---|---|
| Tire type | .951 | .916 |
| Surface | .000 | .000 |
| Speed | .000 | .000 |
| Surface*tire type | .436 | .154 |
| Speed * tire type | .254 | .081 |
| 2-way ANOVA for *obstacle* data | | |
| Tire type | .023 | .105 |
| Obstacle | .000 | .000 |
| Obstacle*tire type | .015 | .000 |

Tukey's pairwise comparisons were used to identify differences in surface and obstacle accelerations. Differences occurred between all surfaces except for rough and smooth concrete (Table 4). Traversing obstacles in the step-up or step-down directions did not produce different accelerations but these obstacles were different than the accelerations produced by potholes (Table 5). These statistical results were the same for both the health and comfort RMS values. Overall, accelerations measured on gravel were the highest and those on concrete were the lowest. Obstacle accelerations were higher than those measured on all surfaces except for gravel.

**Table 4: p-values relating difference in RMS of different surfaces (health & comfort)**

| **Surfaces** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **Asphalt (1)** | -- | 0.00 | 0.00 | <0.03 | 0.00 |
| **Rough Concrete(2)** | | -- | N.S. | 0.0000 | 0.0000 |
| **Smooth Concrete (3)** | | | -- | 0.0000 | 0.0000 |
| **Grass (4)** | | | | -- | 0.0000 |
| **Gravel (5)** | | | | | -- |

**Table 5: p-values relating difference in RMS of different obstacles (health & comfort)**

| Obstacles | 6 | 7 | 8 |
|---|---|---|---|
| **Run with risers (6)** | -- | N.S. | 0.0000 |
| **Run with step-downs (7)** | | -- | 0.0000 |
| **Potholes (8)** | | | -- |

The interaction between obstacles and tire type was significant for both Health and Comfort RMS values. Tukey's pairwise comparison reported significant differences between the comfort RMS values for tire type within the step-down obstacles and potholes (Table 6). Within the step-down obstacles, the Tweel™ technology tires elicited higher accelerations but within the potholes, Tweel™ technology tires produced lower accelerations (Table 6).

**Table 6: Tukey pairwise comparison of obstacles and tires**

| Health RMS values | | | | Comfort RMS values | | |
|---|---|---|---|---|---|---|
| Standard tires | Tweel technology | Sig. p value | | Standard tires | Tweel technology | Sig. P value |
| 3.591 | 3.720 | N.S. | **Riser obstacles** | 3.996 | 4.110 | N.S. |
| 3.627 | 3.878 | 0.023 | **Step-down obstacles** | 3.917 | 4.172 | 0.005 |
| 4.205 | 4.131 | N.S. | **Potholes** | 4.752 | 4.562 | .052 |

Figure 4 and 5 characterize the daily occupational vibration exposure caution zone as set by the ISO 2631-1 standard. Within this zone, care must be taken to avoid potential health risks and, above the zone, health risks are likely. This recommendation is mainly based on exposures for a 4 to 8 hours period (240-400 minutes; shown by the rhomboid box in the figure), and shorter durations need to be analyzed cautiously. The points on the graph mark the lower and upper time levels that a user can traverse different surfaces and obstacles. The results indicate that only low speed mobility on smooth concrete using standard tires falls below the caution zone, while the values for all the other tests conducted on concrete are within the ISO caution zone. All other values are above the upper-bound set by the ISO standard for a 4-hr period (RMS = 1.15 $m/s^2$), suggesting that prolonged exposure to these levels of exposure could have detrimental health affects on the user.

Table 7 and Table 8 characterize the allowable time periods that one can traverse a surface before exceeding the ISO Caution Zone threshold. The results indicate that a wheelchair user can traverse certain surfaces for a long time, but others for only a short duration. For instance, one may travel on concrete for over 2-1/2 hours but traveling on obstacles exceeds the limit in less than 30 minutes. The influence of speed is reflected in the reduced allowable timeframes at the 1.5 m/s speed.

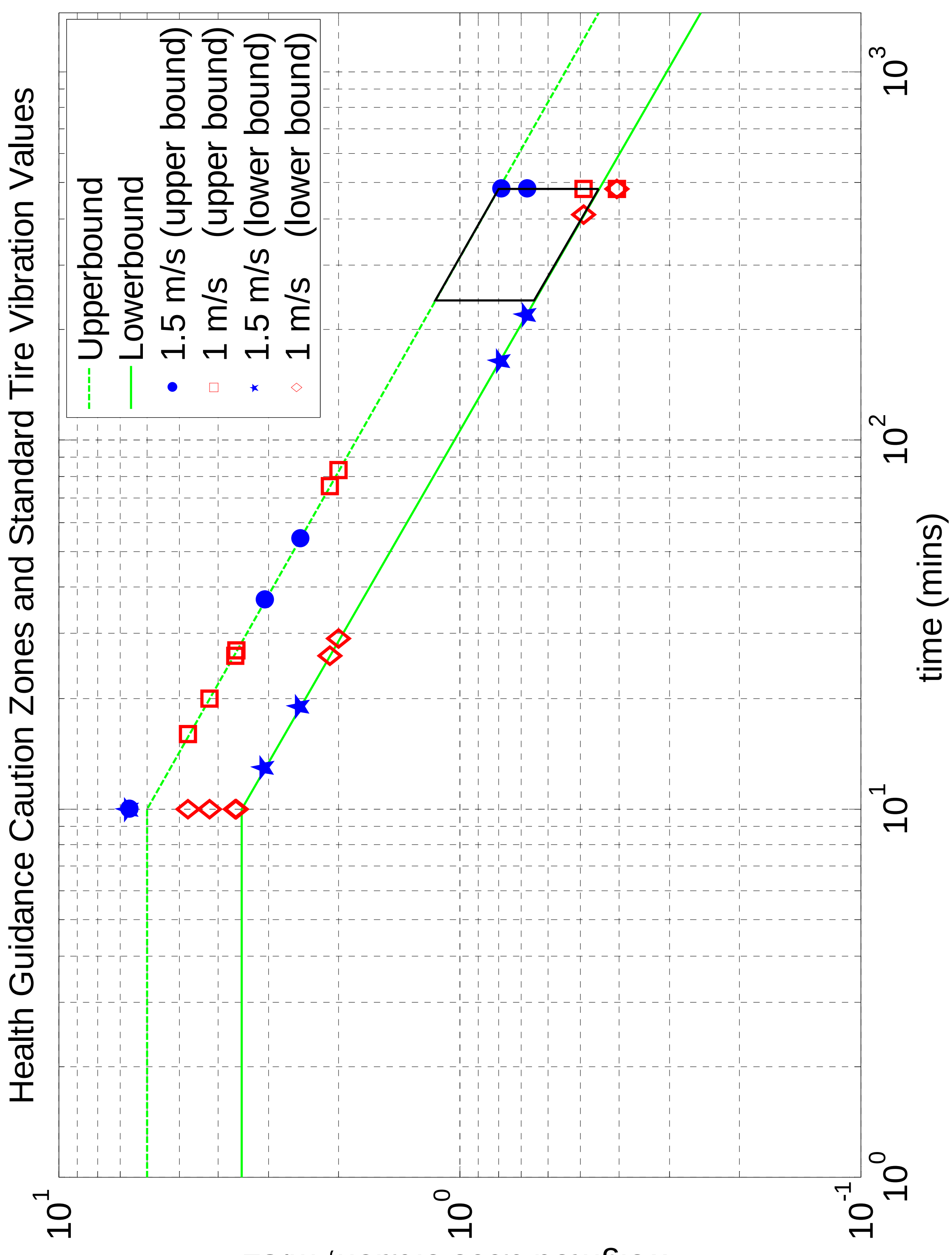



**Figure 4: Exposure caution zone as specified by ISO 2631-1 and standard tire vibrational values**

**Table 7: Caution zone time boundary for the respective surfaces and obstacles in minutes for standard tires**

| **Surfaces/Obstacles** | **Caution Zone time limits for 1m/s (mins)** | **Caution Zone time limits for 1.5 m/s (mins)** |
|---|---|---|
| Asphalt | 29-83 | 19-54 |
| Rough Concrete | > 410 | > 165 |
| Smooth Concrete | > 480 | > 220 |
| Grass | 26-75 | 13 – 37 |
| Gravel | <16 | <10 |
| Obstacles run with riser | <27 | |
| Obstacles run with step-down | <26 | |
| Obstacle run with potholes | <20 | |

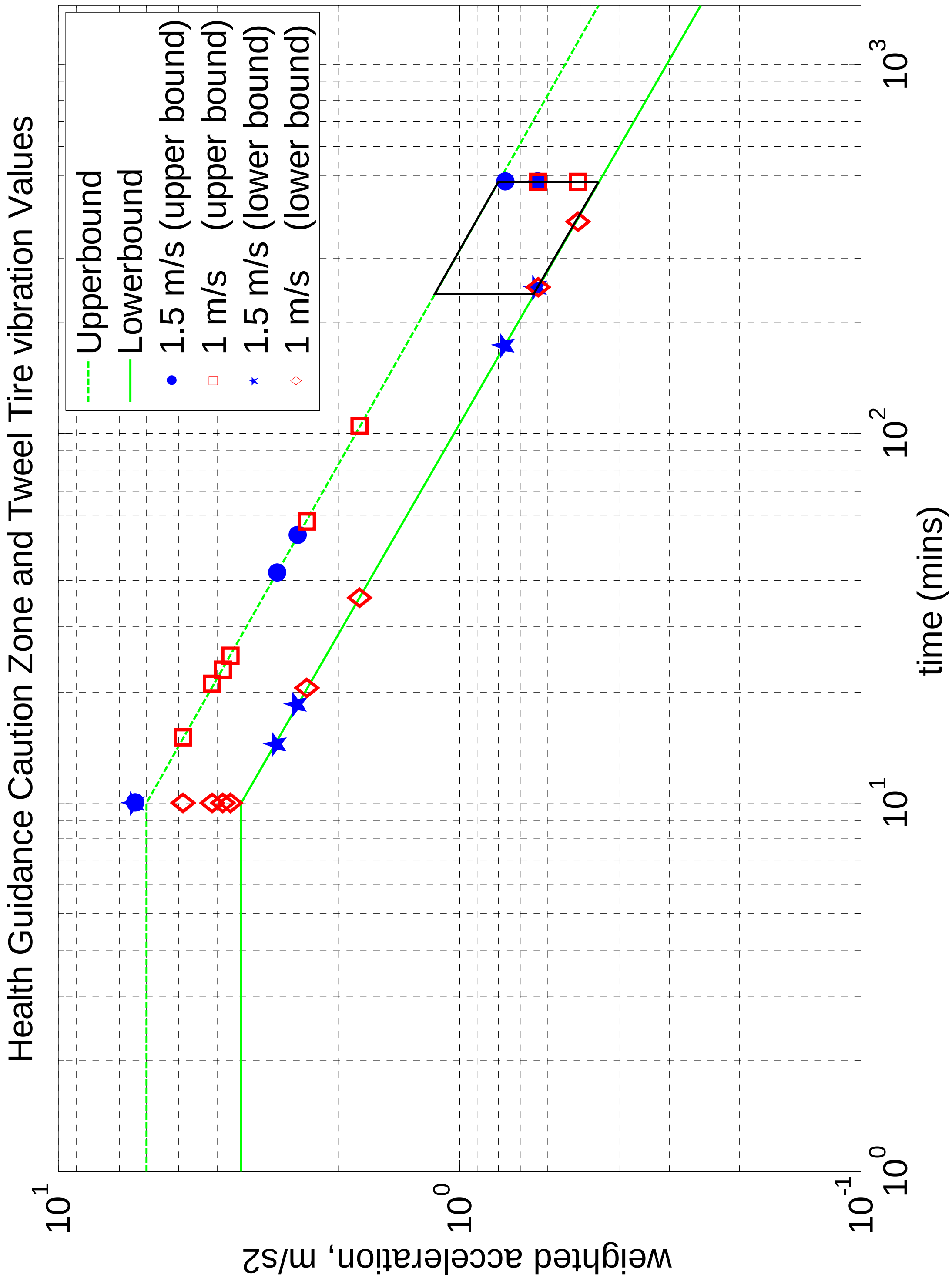



**Figure 5: Exposure caution zone as specified by ISO 2631-1 and Tweel™ technology tire vibrational values**

**Table 8: Caution zone time boundary for the respective surfaces and obstacles in minutes for Tweel™ technology tire**

| Surface/Obstacles | Caution Zone time limits for 1m/s (mins) | Caution Zone time limits for 1.5 m/s (mins) |
|---|---|---|
| Asphalt | 20-58 | 18-53 |
| Rough Concrete | >250 | >174 |
| Smooth Concrete | >375 | >250 |
| Grass | 36-105 | 14.5-42 |
| Gravel | <15 | <10 |
| Obstacles run with riser | <25 | |
| Obstacles run with step-down | <23 | |
| Obstacle run with potholes | <21 | |

The comfort level range prescribed by the ISO 2631-1 standard and the RMS results from this study are listed in Table 9 for both tires. The RMS values experienced by the wheelchair user are significantly high crossing the "Extremely Uncomfortable" boundary for Gravel and Obstacles. Furthermore, even in the best case scenarios the comfort level is still in the "fairly uncomfortable" range.

**Table 9: Perception of comfort as experienced in public transport**

| Comfort level | RMS Values | Surfaces/Obstacles |
|---|---|---|
| Not Uncomfortable | Less than $0.315 m/s^2$ | |
| A little Uncomfortable | $0.315\ m/s^2$ to $0.63\ m/s^2$ | |
| Fairly Uncomfortable | $0.5\ m/s^2$ to $1\ m/s^2$ | Concrete (low speed) |
| Uncomfortable | $0.8\ m/s^2$ to $1.6\ m/s^2$ | Concrete (High speed) |
| Very Uncomfortable | $1.25\ m/s^2$ to $2.5\ m/s^2$ | Asphalt, (low speed - standard), Grass (low speed - Tweel™) |
| Extremely Uncomfortable | $> 2\ m/s^2$ | Asphalt (low speed – Tweel™, High speed), Grass (Low speed – Standard, High speed), Gravel, All Obstacles |

### 2.1.5 Subjective Testing

To get a subjective view on the difference between the two tires, a Michelin trained car driver rode the wheelchair over different surfaces to evaluate comfort differences. Although the driver did not prefer one set of tires over the other, he noted a few differences in vibration transmitted through the two sets of tires. He noted that he could feel the small changes in road surface more while driving on Tweel™ tires; however, the Tweel™ tires dampened the shocks from larger bumps more effectively than the standard tires.

### 2.1.6 Discussion

Tweel™ technology tires did not perform as expected during the testing. Although there were minor differences in the average RMS values for different surfaces, the Tweel™ technology tires failed to produce any significant difference. Even though a difference was noted for health effects for obstacles, the Tweel™ technology tires performed worse than the standard tires. However, the difference in vibrational values was less than 5%.

The dampening qualities of the Tweel™ technology tires can be altered by changing the composition of the materials used. As reported during the subjective testing, the Tweel™ technology tires were effective in damping larger vibrations due to their ability to deform. However, more of the higher frequency vibrations due to small changes in the road were transmitted to the wheelchair. This problem could be addressed by changing the type of rubber used for the tread of the drive wheel, as this layer of material generally dampens out the higher frequency vibrations. This rubber was composed of a much harder material when compared to the solid foam-core tires, therefore changing the composition of this rubber would help improve the dampening properties of the Tweel™ technology tires.

A more important implication of this study is the potential health hazard to wheelchair users from everyday mobility. The results of the health effects and comfort level of the users are discussed in further detail for standard tires in the following section.

#### 2.1.6.1 *Health effect and perceived comfort (standard tires)*

The results reported in this study corroborate with the findings that have been previously reported in the literature. The rough concrete surface used in this study was similar to the poured concrete surface described by Cooper et al. (18) and resulted in similar RMS values. The 8-hr exposure limit was crossed for all of the surfaces except for concrete at low speed. Moreover, the allowable timeframes on certain surfaces (Table 7 and Table 8) helps inform users about their specific level of risk.

The magnitude of acceleration exposure and allowable time of exposure can be compared to power mobility usage to better discern risk. Cooper et al. (14) monitored the power wheelchair usage of 17 participants from two groups- typical users and competitive athletes. Over a 5 day period, users traveled an average of 1667±1414 m and 3432±1741 m per day in the respective groups. The average speed was less than 0.6m/s for both the groups with maximum wheelchair speed being attained for only a few meters at a time. The study also suggested that the maximum a distance a user would potentially travel in day would be 8,000 m. A study conducted by Sonenblum et al. (15) monitored 11 power wheelchair users for 1-2 weeks and showed similar results. The average daily distance traveled was 1394±1490 m with the median being 1100m and the average speed was less than 0.6 m/s. The maximum distance traveled in a single day was 10,600 m traveled at approximately 1.3 m/s for a total time period of 2.25-hrs. These studies suggest that the average power wheelchair user is in motion less than 1-hr per day.

This limited usage appears to suggest that whole body vibration limits would not be exceeded by most powered wheelchair users. However, by applying equation 8 to a profile of surfaces, a more realistic and individualized risk can be calculated. For example, consider a wheelchair user who averages 1 m/s over a combination of surfaces, including smooth indoor surfaces (30%), concrete (30%) and asphalt (30%) and a few obstacles (10%). The equivalent vibration magnitude would be approximately 1.66 $m/s^2$ resulting in cautionary usage limits of 45-120 minutes over this acceleration profile. This particular wheelchair user could then judge her everyday usage to determine if it approaches these limits. Given the time boundaries listed in Tables 2.7 and 2.8, one can assume that certain heavy duty users would exceed the limits. However, simply avoiding exceeding the whole body vibration limits set by 2631-1 may not preclude injury.

Long term exposures (daily over years) of vibration levels within the caution zone prescribed by the ISO standard may result in an elevated risk of health impairment. McGill argues in his review of low back pain biomechanics that the accumulation of low load exposure, including sitting, is a primary contributor to back injury (23). Injuries caused by whole body vibration are well defined for workers in trucking, aircraft, helicopter, maritime and construction industries (24). Research in these industries has shown a correlation between vibration exposure and the risk of back injuries. Furthermore, the biomechanical properties of certain wheelchair users may be different than non-wheelchair users and these differences may predispose a person to low back injury.

The comfort level range defined by the ISO 2631-1 standard (Table 9) were developed for riders on public transit vehicles in an attempt to link comfort with whole body vibration. Applying these limits to wheelchair usage may inform us about the potential impact of wheeled mobility on comfort. While vehicle accelerations do not necessarily mimic those in wheeled mobility, the data indicate that comfort levels are being exceeded.

This study had several limitations that may impact interpretation and generalization of the results. Tests were conducted by a single user on a single wheelchair and accelerations were measured underneath the wheelchair cushion. These were volitional decisions made to permit the study of surfaces without confounding factors. Therefore, the results may differ across wheelchair design or wheelchair user. Furthermore, some wheelchair cushions might dampen certain accelerations thereby reducing vibration exposure although recent research did not find this to be the case (17).

## 2.2 Traction

The rubber tread on the drive wheels was designed to provide better traction; consequently, traction tests described below were conducted on the tires.

### 2.2.1 Test method

Traction testing was conducted by traversing along a banked turn whose angle of inclination increased with distance with a maximum incline of 28° (Figure 6). The wheelchair was driven along this banked turn until it lost traction and slipped downwards. The test was repeated using both sets of tires. Water was then poured over the surface with a hose and the tests were conducted while a constant stream of water was flowing over the surface. To test tire traction while going up an incline, the wheelchair was driven perpendicular to the banked-turn at specific locations so that the incline angle increased with each trial. The test was repeated until the wheelchair failed to climb the incline under both wet and dry conditions.

**Figure 6: Banked turn used for traction testing.**

### 2.2.2 Instrumentation:

A six axis inertial measurement unit (IMU; Racelogic IMU 01) containing 3 MEMS G-sensors and 3 MEMS Yaw-rate sensors was used for this testing along with the GPS system used in previous testing. The IMU was attached on the top of the wheelchair battery compartment with Velcro tape. The Battery compartment extends out underneath the chair, therefore the position of the IMU was under the user and approximately on the axis of rotation of the wheelchair (Figure 7). The maximum available sampling rate of 100Hz was used.

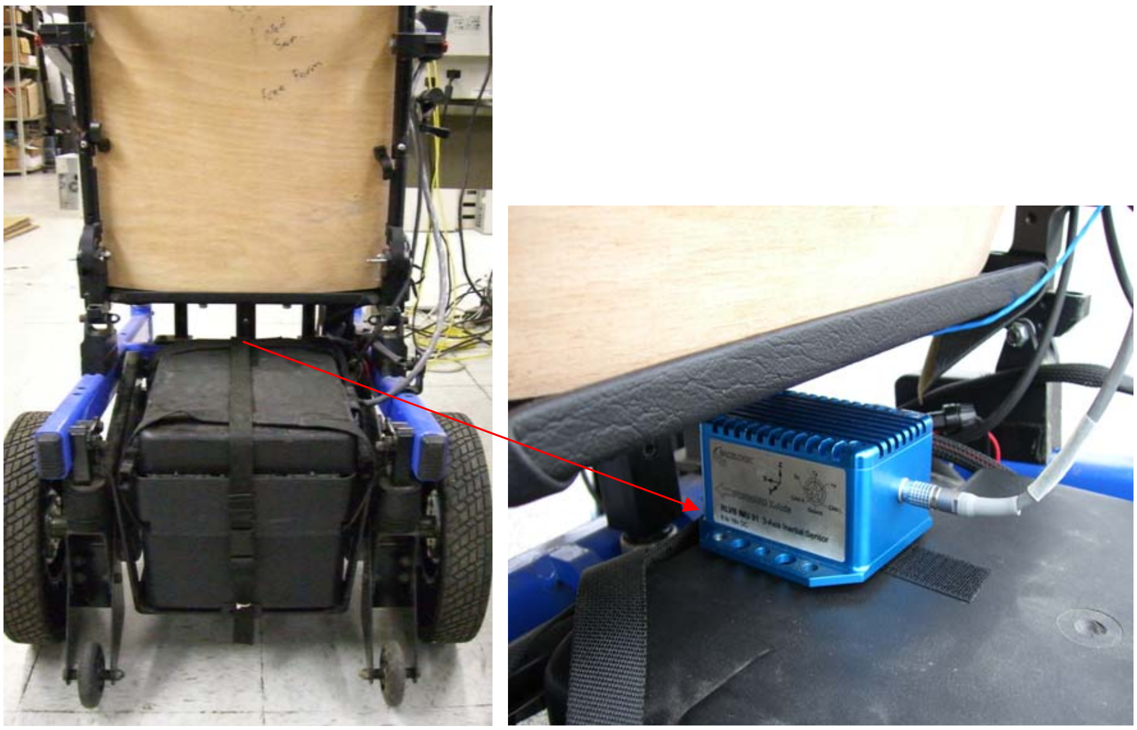


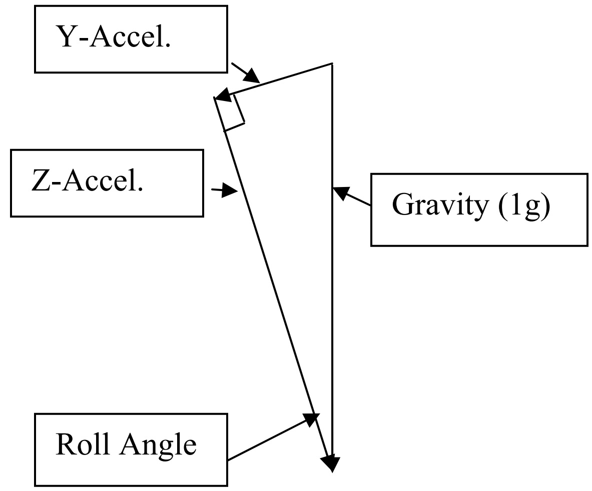
**Figure 7: IMU mounting**

### 2.2.3 Data Analysis

The objective of the traction testing was to compare the level of grip between the two tires under dry and wet conditions. This was achieved by determining the angle of inclination at which the wheelchair started slipping while traversing along a banked turn. The Y (sideways) and Z (vertical) axes acceleration were used to determine the angle of incline for the wheelchair (Eq.9) and a check factor was used to determine the accuracy of the result (Eq.10).

$$\theta = ATan\left(\frac{a_y}{a_z}\right) \qquad (9)$$

$$\sqrt{a_y{}^{\wedge 2} + a_z{}^{\wedge 2}} = 1.0g \qquad (10)$$




θ = Roll Angle

$a_y$ = Y acceleration

$a_z$ = Z acceleration

Yaw rate values were used to identify the point of slippage- the point at which traction was lost. Loss of traction had to be distinguished from yaw tendency produced by the downward turning tendency of the wheelchair. Loss of traction was defined using a yaw rate threshold of 10°/s. This threshold was defined by analyzing yaw values during stable motion.

Stable motion was defined by analyzing yaw-rate values over the time span between 10-20 seconds. This timeframe was determined via investigator experience, review of video tapes, and yaw acceleration profiles. Across all eight data collection trials, the average yaw-rate over this timeframe was approximately 0°/s (0.01) with an average standard deviation of 3.3°/s. A threshold at 10°/s represents a value that is approximately 3 standard deviations above the mean so avoids transient spikes in the yaw rate caused by wheelchair controller adjustments or slight changes in direction from the downward turning tendency.

The angle at which traction was lost was calculated using the Y and Z accelerations. This required the use of stable yaw rate values. A stable yaw rate- defined as a yaw acceleration <5º/sec for ≥ 2 s - was used to define the point in time immediately before slippage occurred. Y& Z accelerations in the middle of this time frame (100 points) were used to calculate the side slope angle. Plots of yaw accelerations are shown in Figure 8 and Figure 9 for the Tweel technology and standard tires, respectively. A complete set of acceleration graphs are included in Appendix E.

To corroborate the angle calculation, the mean and standard deviation of the check factor was calculated (Equation 10; the Y and Z accelerations used for this calculation had units of g). Acceleration values in the middle of the region defined as stable movement (100 data points) were used to check if they added up to '1.00 g'. The result was considered valid if the mean check value was 1.00 g ± 0.02 g and the standard deviation was less than 0.05 (5% coefficient of variation). If an unstable region was picked- defined as a not meeting the above criteria- the defined area would be shifted incrementally until a stable region was found. The trends shown under wet conditions by both sets of tires were similar to their respective trends in dry condition.

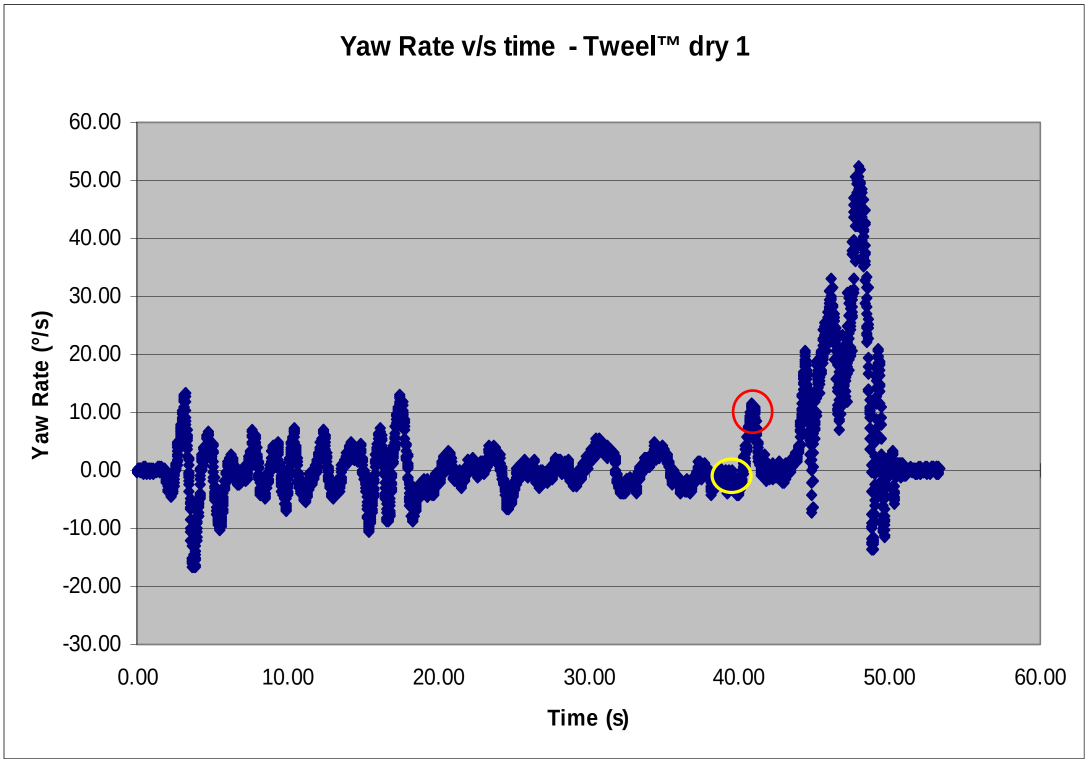



**Figure 8: Tweel™ technology tires yaw rate v/s time**

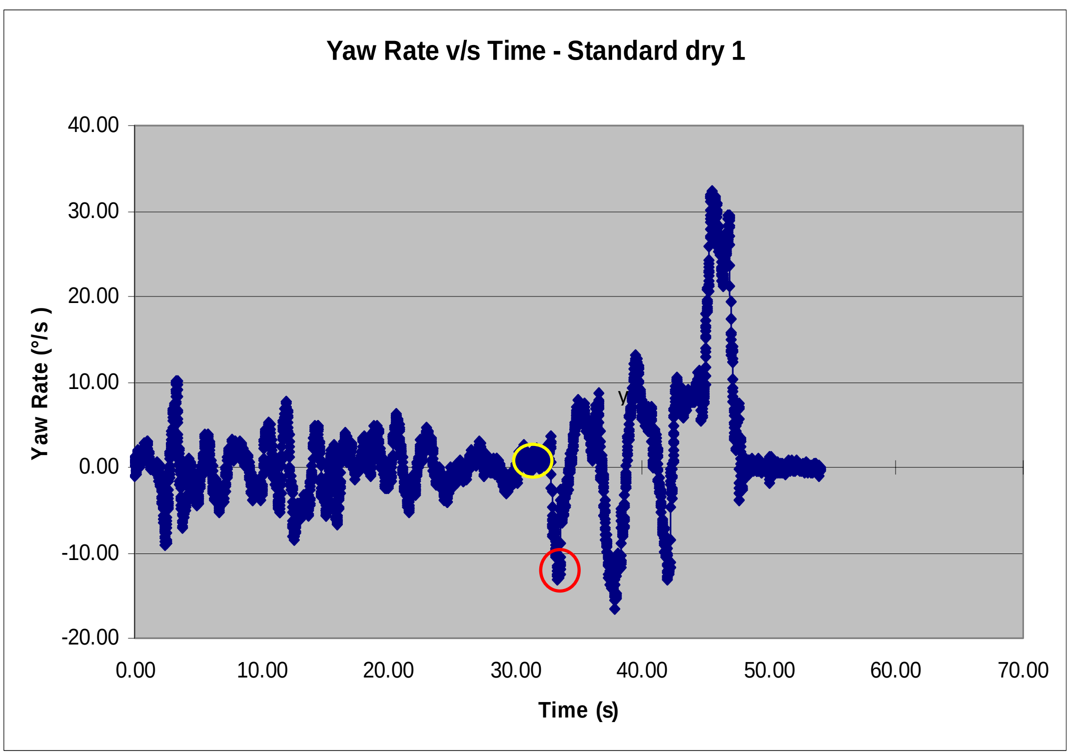



**Figure 9: Standard tires yaw rate v/s time**

### 2.2.4 Results

As observed during testing the Tweel™ technology tires performed marginally better than the standard foam core tires in dry conditions, but were significantly better in wet conditions. The angles of inclination at which the wheelchairs slipped are shown in Table 10 verify those results.

**Table 10: Angle of inclination at slippage during traction testing**

| | Standard tire | | | Tweel™ technology tires | | |
|---|---|---|---|---|---|---|
| | 1st run (°) | 2nd run (°) | Mean (°) | 1st run (°) | 2nd run (°) | Mean (°) |
| Dry | 15.7 | 14.3 | 15 | 15.7 | 15.4 | 15.55 |
| Wet | 14.3 | 14.4 | 14.35 | 15.8 | 16.6 | 16.2 |

As observed while testing the two tires showed different patterns of traction loss. The standard tires experienced constant sideways slippage after a point as it traversed along the turn before it completely lost grip and slid downwards. This can be verified from Figure 10 which shows that there is no dramatic change in angle and the trend-line (moving average) has a few bumps signifying slight slippage with time before failing completely. While on the other hand the Tweel™ technology tires maintained a much better grip on the surface before suddenly loosing grip. This phenomenon can be clearly seen from Figure 11 which shows the angle v/s time change drastically around 45s when the tires fail. The huge fluctuation in angle is due to the fact that Y-axis acceleration was used to calculate angle, which increases dramatically due to the effects of slippage.

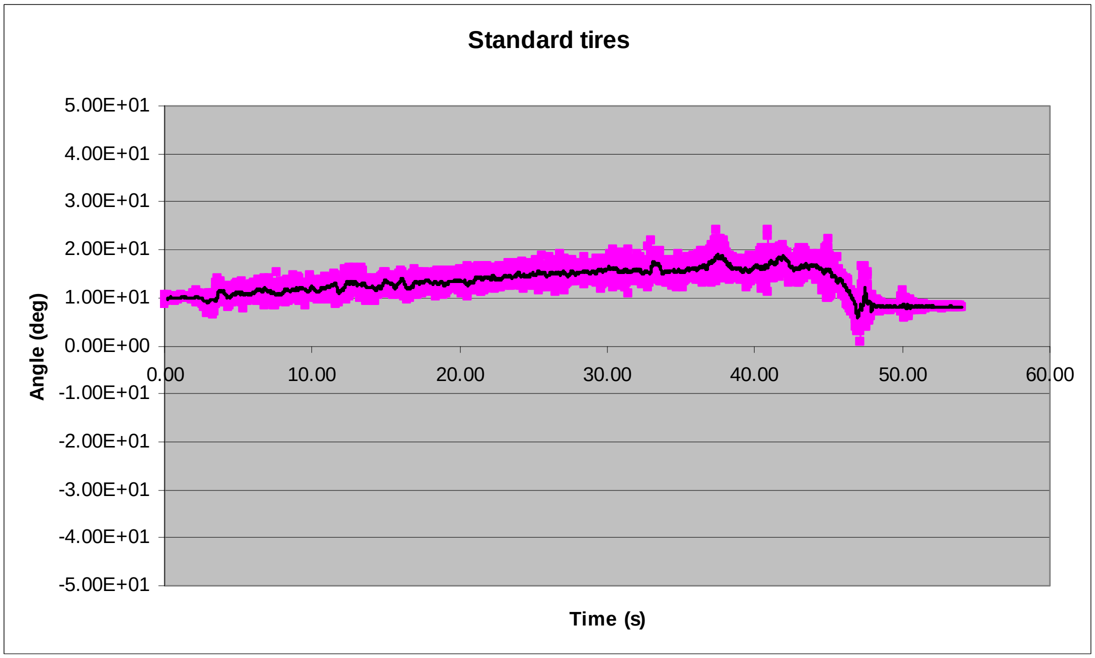



**Figure 10: Angle of inclination v/s time standard tires**

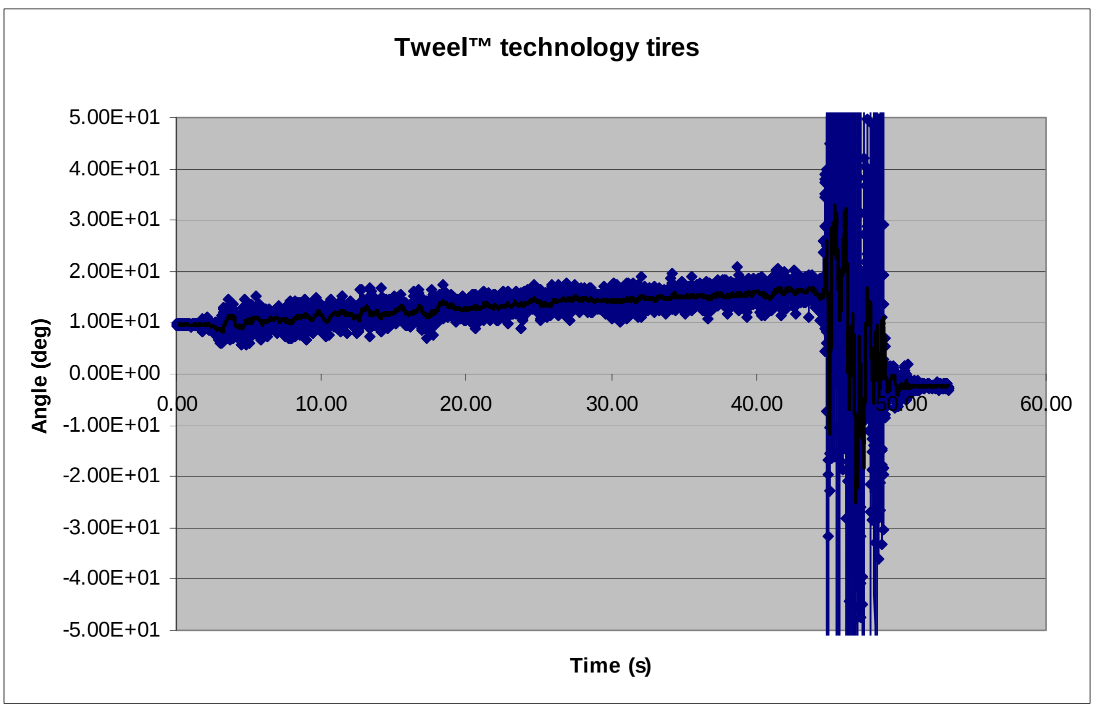



**Figure 11: Angle of inclination v/s time Tweel™ technology tires**

One unusual discovery was that the Tweel™ technology tires performed better in the wet than dry over the two trials. However this could not be statistically verified with more tests as water had already been poured over the surface and due to time constraints more dry runs could not be performed.

Alternatively, tests for climbing an incline plane under wet and dry conditions did not show any significant difference between the two tires. The tests were conducted until the wheelchair operator no longer felt safe driving up the incline. The angle of inclination was approximately 19° at that point and the wheelchair had started tipping backwards, prompting the operator to stop the test. Both sets of tires successfully completed the tests till that point. The contact patch (Figure 12, Figure 13) of the tires on the ground might explain the differences in the grip of the tires and the differences in results between the two tests.

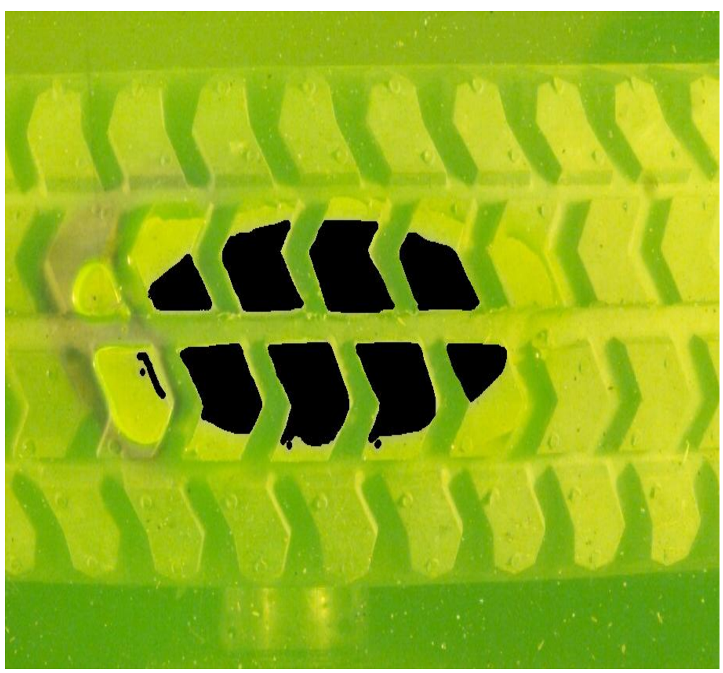


**Figure 12: Standard tire contact patch**

**Figure 13: Tweel™ drive wheel contact patch**

The contact surface area for the Tweel™ is slightly higher at 7.2-$cm^2$ as compared to 6.8-$cm^2$ for the standard tire providing the Tweel™ tires with a better grip. Additionally, it can be seen from Figure 12 that the standard tire has and long oval contact patch to the ground similar to a bicycle wheel. On the other hand the Tweel™ drive wheel has a more round and horizontally wider patch to the ground (Figure 13) similar to a car wheel. This might be the reason why the Tweel™ tires have better sideways traction compared to the standard tire as they have a wider contact area in that direction.

### 2.3 Conclusion

The Tweel™ is a promising technology; however work needs to be done to improve the design and material properties. Although there were differences in the average RMS values for different surfaces the Tweel™ tires failed to produce any significant difference. A combination of asphalt and rough concrete would result in approximately the same levels of vibrations for both sets of tires. Furthermore while Tweel™ tires performed better than standard tires while traversing potholes, they performed worse over riser type obstacles.

If the Tweel™ technology tires can be re-engineered to have better dampening properties, leading to lower vibrational levels on different surfaces it could prove to be a more viable option. Furthermore that coupled with the fact that the Tweel™ technology tires proved to be a significantly better option for wet and dry traction the Tweel™ tires could become the next industry standard.

# CHAPTER 3

# FORCE LOSS AND DAMAGE IN TWEEL™ CASTERS AND DRIVE WHEELS DURING A FIELD TRIAL

Tweel™ technology tires are designed to work under 10% deflection of their radial distance. Therefore, the purpose of this study was to measure the Force-Deflection properties of Tweel™ technology tires before and after field trials to determine deterioration in material properties after use. Furthermore, the Tweel™ technology tires were also inspected for visible damages after the field trial. Nine power wheelchairs were fit with Tweel™ casters and/or drive wheels for a month-long trial. One additional subject used the Tweel™ tires for 3 months. A total of 22 casters and 10 drive wheels were evaluated.

## 3.1 Methods

### 3.1.1 Apparatus

A Zwick/Roell Z005 testing machine was used to measure force-deflection response of the Tweel™ casters and drive wheels. The Zwick can apply a maximum load of 5000 N (AST load cell) at a maximum speed of 500 mm/min, which far exceeded the requirements for this study. The Tweel™ tires were attached by a rod passing through the center, such that they were free to rotate about the rod (Figure 14). However, the fixture prevented any lateral movements of the Tweel™ wheels.

**Figure 14: Tweel™ caster fixture.**

### 3.1.2 Test

The Tweel™ tires were marked with a number to keep a record for future references. The casters were labeled on the inner surface of the urethane ring with a soldering iron, while the metal hubs of the drive wheels were embossed with the respective part number. Two locations on each caster and drive wheel were noted where the load was applied during testing. For this purpose the markings etched into the product during manufacturing were used. This labeling procedure is documented in Table 11.

**Table 11: Location of numbering and testing locations**

| Tweel™ Type | Numbering Location | Testing locations |
|---|---|---|
| Caster | On side A, underneath the point which is marked with "Michelin Tweel" | At the point where it was numbered and 90 deg from it where it states "max load". |
| Drive Wheel | Embossed on the hub with a metal stamp | At the point where it's marked "Michelin Tweel" and 90 deg from this point where it's marked "6202-1" |

The force-deflection test was conducted at standard room temperature and humidity. The test specimen was pre-loaded with 5N and the initial radius was measured. This radius was used to determine the percent deflection required for load-deflection testing. The Tweel™ was then pre-conditioned by compressing it by 15% of the deformable material thickness. The load was applied at 50mm/min and then removed at the same rate. The process was repeated 3 times with no pause between the cycles.

The Tweel™ tire was allowed to rest for 1 min before the compressive force was applied at 50mm/min. The Tweel™ tire was deflected by 10% of the initial radial distance for the casters and 10% of the urethane height for the drive wheel. The load was then removed at the same rate at which it was applied. The force values at 5% and 10% deformation were recorded. The test was repeated at 90 degrees from the spot of the original test to check for discrepancies in tire properties.

## 3.2 Data Analysis and Results

Statistical evaluations were performed to determine the difference in material properties at the 2 test locations, differences between pre and post field trial use and the relationship between material properties and distance traveled. Differences are reported for all tests having a $p<0.1$ significance level calculated from the T-tests.

A paired t-test was conducted to determine whether the order of testing the two locations had any effect on the results. The mean force required to deflect the material by 5% or 10% was lower at Location 2 than Location 1. T-test analysis showed significance at the $p<0.1$ level for the pre- and post-test at 5% deflection and the 10% deflection during the pre-test. The test results are listed in Table 12. Significant differences were not found with the drive wheels as shown in Table 13. These results indicate that an order effect might have influenced the results of testing the 2 locations but these differences were minor (non-significant and <1%) for the drive wheels and fairly small (approximately 1%) for the casters. Because testing was conducted in the same order before and after the field trial and the down time between the testing of the locations was the same in both cases, any residual effect would have been approximately the same during pre- and post-testing. Therefore, both locations were used for subsequent analyses.

**Table 12: Pre and post test force values at 5% and 10% for casters**

| Casters | Pre 5% | | | Pre 10 % | | |
|---|---|---|---|---|---|---|
| | Location 1 | Location2 | P val. | Location 1 | Location 2 | P val. |
| Mean | 385.16 | 381.30 | 0.057 | 599.05 | 594.02 | 0.088 |
| Stdev. | 38.69 | 40.33 | | 59.57 | 60.06 | |
| | Post 5% | | | Post 10 % | | |
| | Location 1 | Location2 | P val. | Location 1 | Location2 | P val. |
| Mean | 338.45 | 335.59 | 0.099 | 529.65 | 525.83 | 0.252 |
| Stdev. | 47.08 | 47.44 | | 63.56 | 65.59 | |

**Table 13: Pre and post test force values at 5% and 10% for drive wheels**

| Drive Wheel | Pre 5% | | | Pre 10 % | | |
|---|---|---|---|---|---|---|
| | Location 1 | Location2 | P val. | Location 1 | Location 2 | P val. |
| Mean | 710.73 | 708.63 | 0.688 | 1125.11 | 1119.13 | 0.474 |
| Stdev. | 30.46 | 25.56 | | 46.11 | 39.06 | |
| | Post 5% | | | Post 10 % | | |
| | Location 1 | Location2 | P val. | Location 1 | Location2 | P val. |
| Mean | 625.79 | 620.26 | 0.219 | 1005.82 | 996.29 | 0.127 |
| Stdev. | 28.91 | 27.43 | | 48.54 | 42.04 | |

The mean, standard deviation and coefficient of variation of the force required to compress the Tweel™ technology tires by 5% and 10% was calculated as shown in Table 14 and Table 15. For Tweel™ casters, the coefficient of variation before the field trial was about 10% indicating some variance across casters. The coefficient of variation for Tweel™ drive wheels was much lower at 3%, suggesting better uniformity in material properties over the set.

The post field trial data shows that the mean force had fallen in all cases by an average of more than 10% at both 5% and 10% deflection levels. Force loss in casters ranged from about 1% to 50%. A paired t-test comparing the caster pre- and post- force values was significant at $p<0.001$ for both 5% and 10% deflections. Force loss in drive wheels ranged from 9% to 14% at 5% deflection and from 8% to 14% at 10% deflection. A paired t-test comparing the drive wheel pre- and post- force values was significant at $p<0.001$ for both 5% and 10% deflections This force loss can be considered a significant change because the field trial was only conducted over a 30 day period. The coefficient of variation in all of the cases increased in the post field trial testing showing that the wear differed across Tweels™, which was expected as they were driven under different conditions and distance. A Complete set of the data is tabulated in Appendix F.

**Table 14: Force required to deform casters by 5 and 10%**

| Casters | Mean force (N) 5% | Std. 5% | Coefficient of variation | Mean Force (N) 10% | Std. 10% | Coefficient of variation |
|---|---|---|---|---|---|---|
| Pre | 383.23 | 39.08 | 0.101 | 596.53 | 59.13 | 0.099 |
| Post | 337.02 | 46.71 | 0.138 | 527.74 | 63.81 | 0.120 |
| Difference | 46.21 | | | 68.79 | | |
| % Difference | 12.1 % | | | 11.5 % | | |

**Table 15: Force required to deform drive wheels by 5 and 10%**

| Drive Wheels | Mean force (N) 5% | Std. 5% | Coefficient of variation | Mean Force (N) 10% | Std. 10% | coefficient of variation |
|---|---|---|---|---|---|---|
| Pre | 709.67 | 27.38 | 0.0385 | 1122.12 | 41.70 | 0.0371 |
| Post | 623.02 | 27.57 | 0.0442 | 1001.05 | 44.46 | 0.0444 |
| Difference | 86.65 | | | 121.07 | | |
| % Difference | 12.2% | | | 10.78% | | |

The relationship between force loss and distance traveled was investigated using a simple correlation for casters since most of caster were used for approximately 40 miles during the field trial. A correlation factor 0.33 was obtained, showing a weak dependence of loss in force deflection due to distance traveled. This infers that distance is not the only factor that contributed to force loss in casters and other variables, such as environment of use may have influenced the results. In fact, the subject whose casters experienced the highest force loss regularly used his wheelchair at construction sites.

Linear regression analysis was used for the drive wheel data as the distance traveled was much more spread out for the different user. The drive wheels showed a strong relationship between force loss and distance traveled ($R^2$ =0.635; regression available), as shown in Figure 15. In contradistinction to the caster data, this relationship illustrates a stronger influence of distance traveled on the force loss of drive wheels.

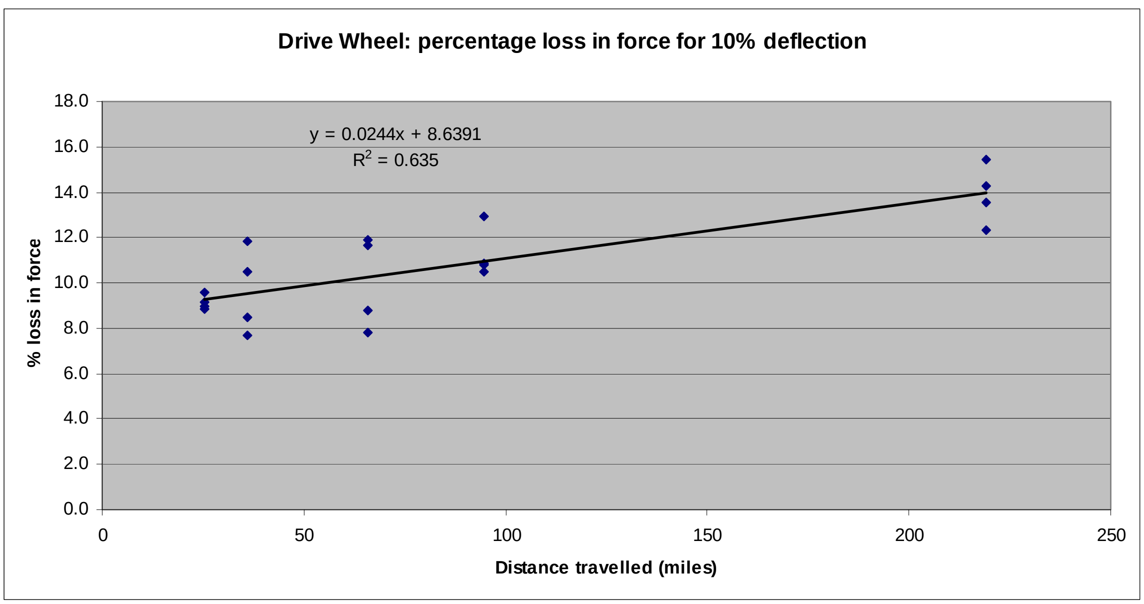



**Figure 15: Percent reduction in force required at 10% deflection in drive wheels with respect to distance traveled**

**Note: each point represents a single drive wheel**

The average force loss in casters traveling 40 miles or less was about 7% and the force loss of drive wheels traveling less than 40 miles was 9%. This early loss in stiffness accounts for a high percentage of overall force loss, i.e., the average force loss for all drive wheels was 11%. Part of this force loss could be associated with a loss of material from the wear and tear shown in section 3.3. However, there level damage reported for majority of the tires was significantly low to account for over 7% loss in force.

Therefore, the force loss could be associated with permanent deformation of the tires. During regular operation a small part of polyurethane the fin could be deflected beyond its elastic level, thus causing plastic deformation on that micro-level. Over time this region of material that has been plastically deformed would increase, as the micro regions that have been plastically deformed no longer support the initial force from the deflections. Furthermore, higher impacts would increase the rate of this deterioration, as larger sections would get plastically deformed from higher levels of deflection. This is consistent with the results from the field trial as the user whose casters had the highest force loss regularly used his wheelchair at construction sites and permanent plastic deformation could be seen on the fins of the casters (Figure 17 a).

While the data set is limited, the differences in the regression analysis illustrate the different roles of casters and drive wheels. Casters are exposed to many different types of forces and stressors since they are of smaller diameter and impact obstacles during everyday mobility. Drive wheels are better equipped to negotiate barriers so fatigue is more related to distance.

### 3.3 Visible Wear and Damage Inspection

Most of the drive wheels and casters did not show significant visual damage. However, all of the Tweel™ drive wheels had lost some parts of the tread. In most cases it was on the outer edge of the wheel as shown in Figure 16. Some of the drive wheels also lost tread in the middle of the tire. This could affect the long term use of the tire as it would lead to lower traction. The rubber used in Tweel™ drive wheels was a harder compound than what is used in solid foam-cores tires commonly used by wheelchair users. The harder compound might be the reason why parts of the tread were removed in chunks during everyday use, as they did not deform as effectively when hit by small obstacles.

**Figure 16: Extensive tread damage to a drive wheel**

The Tweel™ casters showed less physical damage than the drive wheels after the field trials but, noticeable wear could be seen. In two cases in which casters were subjected to high usage, significant degradation to the materials was visible. The fins on two casters were bent, one caster had a broken fin, and one of the casters developed a flat spot as can be seen in Figure 17 a & b. A Complete set of visual damage report along with user information is in Appendix G.


**Figure 17 a&b: Casters with significant structural damage**

### 3.4 Conclusion

The Tweel™ tires did not perform to the expectations that users have of casters and drive wheels. On average, users replace their casters every 2-3 years with drive wheels being replaced a bit more frequently due to tread wear. The Tweel™ drive wheels and casters showed significant deterioration in material properties (average 10%

reduction in force) over the short field trial. This issue needs to be addressed as durability and life span is an important criterion in choosing replacements wheels for wheelchairs; one of the key reasons why users don't use pneumatic tires.

The Tweel™ casters showed relatively lower signs of visual damages at the end of the trial, but one of the casters had to be replaced due to a flat spot. Although none of the Tweel™ Drive wheels had to be replaced they showed significant loss of tread. This could prove to be important as the tread provides the traction for the wheelchairs. In conclusion, the life span of both the Tweel™ drive wheels and casters needs to be improved before it can be sold to most wheelchair users.

# CHAPTER 4

# DEVELOPMENT AND VALIDATION OF INSTRUMENTATION FOR MEASURING WHEELCHAIR MOVEMENTS

The purpose of this study was to develop and validate instrumentation that measures the distance traveled by a wheelchair, as well as characterizing movements by starts, stops, turns and distance. These activities occur frequently within everyday mobility so their measurement is needed to fully understand wheeled mobility. Moreover, maneuvers that must overcome inertia require the most effort on part of manual wheelchair users, so it is important to identify the frequency and intensity of such activities.

## 4.1 Technology Requirements

Since the purpose of this research is to understand everyday mobility, measurements must be taken on different wheelchairs in different environments of use. This requires that the instrumentation be compatible with different manual and power wheelchair designs and robust enough to withstand everyday use. With these issues in mind, the following design criteria were established for the instrumentation.

- Update the previous definition of a mobility bout defined as; a bout of movement initiated when a user travels a minimum of 0.6 m within 4 seconds and continues until the user travels less than 0.75 m over 14 seconds. The instrument will correctly determine bouts and stops to 90% accuracy.

- Instrumentation should measure starts, stops and turn as people traverse indoor and outdoor surfaces, with an accuracy level of at least 90%. Furthermore it should be able to filter out erratic maneuvers caused by sources other than wheeling (e.g. in vehicle vibration, loading or handling wheelchair etc.).
- Instrumentation should be able to measure distance with a minimum of 90% accuracy and preferably, a 95% accuracy level.
- Instrumentation should be compatible with multiple different manual and power wheelchairs, as the future studies will monitor a large group of people that use different types of chairs. The instrumentation should be installed or uninstalled in less than 15 minutes, with a maximum of 1 hour.
- The instrument must be robust to withstand being attached to the wheelchair for a minimum of 1 week and, preferably for a 2 week time period. The instrumentation should not require recharging during this time frame.
- The new technology should preferably interface with the existing data logger (Levo Science monitor) however a different logger can be used if necessary.

## 4.2 Instrumentation

Multiple technologies were investigated and three were selected for further study, based on their anticipated ease of attachment and reliability. Furthermore, it was decided to use two methods concurrently to determine the cost/benefit from using two methods instead of one a single method. The three sensors were:

- Accelerometer unit on the rim of the tire
- Gyro-Accelerometer under the seat of the wheelchair

- Reed-switches to count wheel revolution

### 4.2.1 Accelerometer on the Rim

The concept of this approach was to place an accelerometer on the wheel of a wheelchair, in order to determine the move distance and to break up movements into bouts of mobility. The alternating acceleration profile that results from the turning wheel was used to count the revolutions of the tire, leading to distance traveled based on the wheel diameter. Secondly, the acceleration profile was used to differentiate between periods of movement vs. non-motion, thus dividing the motion into bouts by determining start and stop times.

In order to verify the usability of this technology a Bluetooth accelerometer unit was used. This unit was comprised of 2 bi-axial accelerometers (ADXL202JE) and a Bluetooth module (Taiyo Yuden) controlled by a PIC chip. The Bluetooth accelerometer unit was attached to the rim of a manual wheelchair drive wheel, with one of the accelerometer axis aligned with the tangential direction of movement of the wheel. A laptop with Bluetooth capabilities was used receive the data from the accelerometer which was sampled at 60Hz.

After the usability of this technology was determined a self contained unit was developed, due to power consumption concerns with Bluetooth technology and the loss of data packets when communicating with the laptop. This new unit contained a data logger (Logomatic Serial SD Datalogger) along with a single tri-axial accelerometer (MMA7260Q) and a Li-Ion battery. Therefore, there was no need to communicate with any other devices.

The data logger contains 10 channels of 10 bit Analog to digital converters (ADC) capable of a sampling frequency of up to 1500Hz for a single channel. In this case the 3 directional channels from the accelerometer were directly connected to the ADC pins of the data logger and sampled at 60Hz. The logger wrote the data to an SD card as a text file that was transferred to a computer to post processing. A single Li-Ion battery rated at 2600mAh was used to power the system, providing a battery life of 30 hours.

### 4.2.2 Gyro-Accelerometer Under the Seat

During the testing a gyro-accelerometer unit was placed under the occupant seat. The purpose of this unit was to detect turns, starts and stops. The gyroscope was used to measure the yaw rotation rate of the wheelchair, while the accelerometer was used to detect the acceleration of the wheelchair in 3 mutually perpendicular directions. The yaw rotation rate was used to detect turns, while the acceleration profile from the direction of travel was used to detect if the wheelchair was moving. The acceleration data gathered from this unit could also be used to determine whole body vibration health effects and perceived comfort levels discussed in previous chapters.

The Gyro-Accelerometer was attached beneath the seat in line with the axis of rotation for the tires and equidistance from the two drive wheels. A similar data logger (Logomatic Serial SD Datalogger) and tri-axial accelerometer (MMA7260Q) were used, along with a gyroscope (ADXRS401). Both the gyroscope and accelerometer were sampled at 60 Hz

#### 4.2.3 Reed Switches

A reed switch is an electronic switch that changes state when a magnet is brought within close proximity of the switch. A non-latching reed switch was used to measure wheel rotation. The switch is closed when a magnet is in close proximity and open otherwise. The combination of reed switches on the frame of the wheelchair and magnets on the wheel was used to detect starts and stops and calculate the distance traveled by the wheelchair.

Two Reed switches were attached to the frame of the wheelchair; one on either side of the chair. Two magnets were attached on each wheel to activate the reed switches every half revolution of the wheel. The distance between the magnets and the switch when the magnet passed by was less than 12.5 mm, as required to activate the switch. The same Logomatic SD Data logger as the gyro-accelerometer unit was used to count the number of times the magnet closed the reed switch. The circuit shown in Figure 18 was used to connect the Reed switch to the logger. This circuit produces a high voltage until the switch is closed, at which point the voltage drops to zero nearly instantaneously. Once the magnet is removed, the voltage starts increasing back to 3.6v.

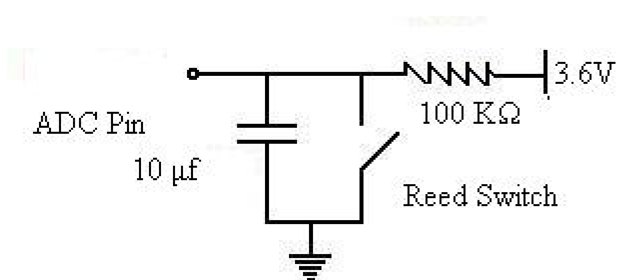



**Figure 18: Circuit diagram used for the reed switches**

## 4.3 Testing

Tests were designed to address all the design criteria listed in Section 4.1, and were grouped together into four areas as follows. 1) Determine what constitutes as a bout of mobility and a turn, 2) Check the accuracy and resolution of the sensors, 3) Validate the effectiveness of each technology in everyday mobility environments, and 4) Check for compatibility with different types of wheelchairs and overall battery life. All the tests were conducted with all three types of transducers attached to the wheelchair, permitting the comparison between technologies. Since prototypes were developed in this phase, robustness testing was deferred until the devices are placed in their final packaging.

### 4.3.1 Bouts of Mobility and Turns

Criteria for different aspects of mobility had to be defined, upon which the sensors would be measured. This included the minimum time of non-movement that would constitute a stop, minimum move distance for a bout and the minimum turn angle over a given period of time that would represent a turn. In order to determine these criteria a wheelchair user was observed for 15 minutes, while performing various tasks indoors that the he considered common to his everyday mobility, as well as short bouts of mobility outdoors. The objective of this observation was to determine the minimum move distance and average turn angles along with the time frame for the turns. Furthermore, various stake-holders were interviewed for their opinions on minimum move distance for a bout, stops time and turns angle.

### 4.3.2 Accuracy and Environment Testing

Multiple tests were developed to check the accuracy and robustness of the sensors to detect the desired aspects of mobility. These consisted of 1) Defined indoor track, 2) Defined outdoor track, 3) Stationary turn test and, 4) Moving turn test. Most of the tests were conducted in a lab environment to facilitate the development of a data analysis method. After the initial phase of testing, more tests were conducted on outdoor surfaces to check the accuracy levels of the initial results on rougher surfaces.

An initial test was conducted indoors to check the accuracy of the sensors in determining start, stops, turns and distance. The first part of the test consisted of riding over a designed path with several stopping points; stop duration varied from 10 seconds to 1 second. Five different able-bodied users were tested, using a manual wheelchair. Users were allowed to propel themselves at a pace they found comfortable for the first part of the test.

For the second half of the test, users were asked to shift their weight in the chair and to transfer out of and back into the chair. This was done to check how vibration from weight shifts and transfers would affect the different sensors. They were also asked to travel a 12.2 m straight line distance at a slow pace. This was done to check if slow movements were above the “stop” threshold for the sensors. The route details of the test are described in Table 16.

**Table 16: Indoor accuracy test path**

| Section | |
|---|---|
| 1 | 12.2 m move in a straight line with 5 s and 4 s stops followed by a 6.1 m move with 2 left turns and a 10 s stop |
| 2 | 12.2 m move in a straight line with 3 s and 2 s stops followed by a 6.1 m move with 2 left turns and a 10 s stop |
| 3 | 12.2 m move in a straight line with 2 s and 1 s stops followed by a 6.1 m move with 2 left turns and a 10 s stop |
| 4 | 12.2 m move in a straight line with 2 s and 1 s stops followed by a 6.1 m move with 2 left turns and a 10 s stop |
| 5 | Weight shifts and transfer 10 s wait |
| 6 | Slow movement in a straight line |

An outdoor course was defined to determine the effect of surface shocks on the results. Asphalt and paved sidewalks were chosen to represent a majority of outdoor surfaces that a user might traverse in a given day. Each trial included few stops and turns, with a pre-defined move distance as described in Table 17.

**Table 17: Outdoor testing path**

| Section | |
|---|---|
| 1 | 4.6 m move in a straight line followed by a right turn on a sidewalk |
| 2 | 45.7 m move in a straight line with a 2 s stop on a sidewalk followed by a right turn onto asphalt |
| 3 | 30.5 m move in a straight line with a 2 s stop on a asphalt followed by a 180° turn and a 10 s wait |
| 4 | Repeat in the reverse direction |

Two additional tests determined accuracy of the sensors to detect turns from a stationary position and while moving. The first test comprised of turning the wheelchair 30° in one direction waiting for 5-10 seconds for the sensors to settle and then turning back 30°. The entire process was repeated 3 times for a total of 6 turns. For the second test the wheelchair was driven in a straight line followed by a 30° turn and then driven in a straight line again for approximately 3 m. The wheelchair was then rotated 180° and the test repeated in the opposite direction after a 10 second pause. The process was also repeated 3 times.

As a final test, sensors were attached to two power wheelchairs to monitor bouts of mobility throughout a day. The objective of this test was to process real-world data and check for unexpected results. The reed switches were not attached in this case as real-world data was available for them from previous studies conducted at CATEA.

### 4.3.3 Compatibility and Battery Life

In order to check for compatibility, the sensors were attached to two different types of manual and power wheelchairs. The common methods of attachments were recorded, along with designs for support structures that would ease the attachment process. Any major difficulties with attachment procedures were also recorded.

A multimeter was used to determine the current drawn by the instrumentations. Subsequently research was conducted on different types of batteries with respective to life span in comparison to the size of the battery.

## 4.4 Data Analysis

Different techniques were used for different sensors; therefore, the analysis methods are separated according to the sensors.

### 4.4.1 Accelerometer on the Rim

Starts, stops and distance traveled were determined from this sensor. All the raw data was initially passed through a low-pass Butterworth filter (4 Hz cut-off) to reduce high frequency noise. A cut-off frequency of 4 Hz was used at it represents the maximum frequency at which the wheel might rotate; for a power wheelchair with a 30 cm wheel diameter it represents a speed of 3.8m/s. After filtering the data, distance was calculated by breaking the data, which looks similar to a sine wave for one full revolution of the wheel, into 2 parts. This effectively counts every time the wheel rotates 180°. A sample data set is shown in Figure 19. Upper and lower thresholds were set up at half the average peaks levels during motion and a script was set up to look for one threshold at a time, as described in the flow chart shown in Figure 20.

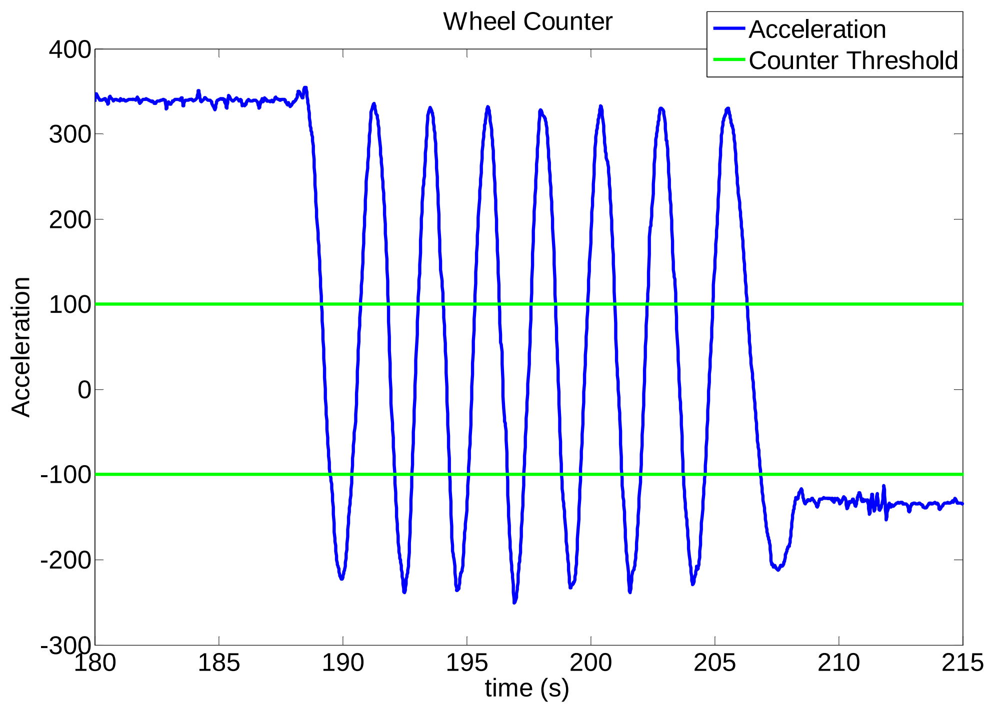



**Figure 19: Sample filtered acceleration profile**

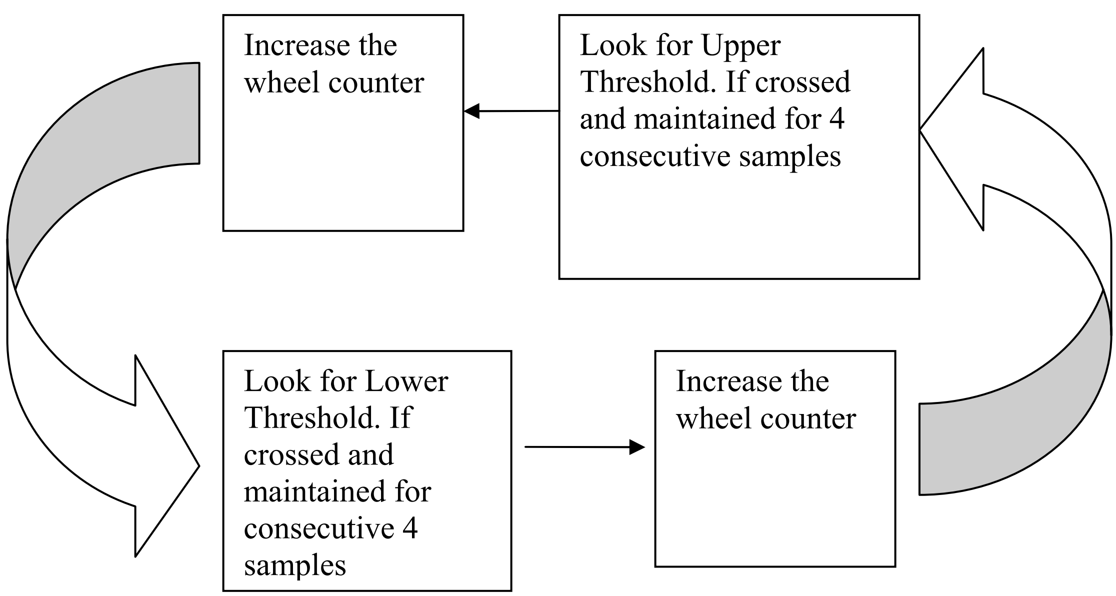



**Figure 20: Flow chart of wheel counter**

In order to determine stops, standard deviation of the filtered data from the accelerometer was calculated over a moving 2 second window. The wheelchair was considered stopped, if the standard deviation fell below the threshold level, which was set at ¼ the average peak levels of the standard deviation while the wheelchair was in motion. On the other hand if it was determined that the wheelchair was moving and the distance between stops was calculated as a bout.

### 4.4.2 Gyro-Accelerometer Under the Seat

Two sets of information were derived from the Gyro-Accelerometer unit that was placed beneath the seat. Firstly, it was used to determine whether the wheelchair was turning and secondly, to determine starts and stops. The raw data from the Gyroscope were integrated using a moving 2 second window to determine if the wheelchair was turning. A turn was defined as yaw rotation of greater than or equal to 30° within a 2 second window.

In order to determine starts and stops, an analysis method similar to the one used for the accelerometer on the rim was applied. The acceleration data from the direction of travel was passed through a low-pass Butterworth filter (4 Hz cut-off) and the standard deviation of filtered acceleration data was calculated over a 2 second window. If this value of standard deviation was above a certain threshold it was inferred that the wheelchair was moving. The cut-off frequency in this case was determined empirically from the current data by iteratively reducing the cut-off level so that the noise level was reduced without having a significant effect on the desired region of data.

### 4.4.3 Reed Switches

The Reed switches closed every time the magnet passed the switch, causing the voltage to drop to zero. The voltage would start increasing as soon as the magnet was outside the range of the reed switch. The number of voltage drops was calculated and since each wheel contained 2 magnets, every drop equated to half a revolution of the tire. However, the direction of wheel rotation could not be determined using this method.

## 4.5 Results

After observing a wheelchair user and discussing the various aspects of mobility with the stake-holders the following standards were set for start, stops and turns.

- Stop: A wheelchair was considered stopped after 2 seconds or more of non-movements.
- Start: A minimum move distance was set at half a revolution of the drive wheel to be considered a bout.
- Turn: A wheelchair had to rotate 30° or more in 2 seconds to be considered as turning.

### 4.5.1 Accuracy and Environment Testing

The performance of the sensors was broken up according to the effectiveness in meeting the standards set for the different aspects of mobility.

#### 4.5.1.1 Distance

The accelerometer unit on the rim and reed switches reported similar results for distance measured during indoor and outdoor testing. The average difference in the distance measured by the 2 sensors was 1.5% with the average difference in the number of counts being 1.7 counts. Both the reed switches and accelerometer increase the counter every half revolution of the wheel, therefore, depending on the location of the wheel when the test was started and finished, there could be a 1 count difference between the two sensors. A list of the total distance measured by the different sensors is given in Table 18.

**Table 18: Distance measured during indoor and outdoor testing**

| **Indoor testing** | **Right wheel** | **Right wheel** | **Left wheel** | **Left wheel** |
|---|---|---|---|---|
| | **Accelerometer unit (m)** | **Reed switch (m)** | **Accelerometer unit (m)** | **Reed switch (m)** |
| User 1 | 94.8 | 95.75 | 87.14 | 91.92 |
| User 2 | 95.75 | 94.8 | 88.09 | 87.14 |
| User 3 | 88.09 | 90.01 | 84.27 | 85.22 |
| User 4 | 92.88 | 91.92 | 83.34 | 83.34 |
| User 5 | 95.75 | 93.84 | 84.27 | 87.14 |
| **Outdoor testing** | | | | |
| User 1 | 151.29 | 153.2 | 155.12 | 154.16 |
| User 2 | 149.38 | 153.2 | 153.2 | 153.2 |
| User 3 | 162.78 | * | 158.95 | 157.04 |

**Table 18 (continued)**

| | | | | |
|---|---|---|---|---|
| User 4 | 157.04 | 156.08 | 152.25 | 152.25 |
| User 5 | 153.2 | 156.08 | 154.16 | 156.08 |

* The magnet was displaced mid-trial

The accuracy level of the sensors was determined by their ability to measure the 12.2 m straight line moves during section 1 and 2 of the indoor testing. It can be seen from Table 19 that the distance measured by the sensors was within one revolution count for both sensors in all of the trials. Thus both the sensors are well within the accuracy level prescribed by the design criteria.

**Table 19: Accuracy testing for distance measurement**

| **Accelerometer Unit** | | | | |
|---|---|---|---|---|
| **Subject** | **Section 1** | | **Section 2** | |
| | Right wheel | Left wheel | Right wheel | Left Wheel |
| User 1 | 12.44 | 12.44 | 13.41 | 12.44 |
| User 2 | 11.49 | 11.49 | 12.44 | 13.41 |
| User 3 | 12.44 | 13.41 | 13.41 | 13.41 |
| User 4 | 11.49 | 12.44 | 11.49 | 12.44 |
| User 5 | 12.44 | 12.44 | 11.49 | 13.41 |
| **Reed switch** | | | | |
| **Subject** | **Section 1** | | **Section 2** | |
| | Right wheel | Left wheel | Right wheel | Left Wheel |
| User 1 | 12.44 | 12.44 | 11.49 | 12.44 |

**Table 19 (Continued)**

| | | | | |
|---|---|---|---|---|
| User 2 | 11.49 | 11.49 | 12.44 | 12.44 |
| User 3 | 13.41 | 12.44 | 13.41 | 12.44 |
| User 4 | 11.49 | 11.49 | 11.49 | 11.49 |
| User 5 | 11.49 | 12.44 | 13.41 | 13.41 |

Few problems were encountered during the tests. A magnet was displaced on the right wheel during one of the trials and was adjusted at a later time during the trial resulting in an apparent 42.9 m error in the reading. The result from that test was not included in the statistical analysis. Furthermore, during one of the trials the magnet was close to the sensor during the weight shifts and a few extra counts were recorded by the reed switch in that trial. Both the sensors meet the design criteria for accuracy; however, the accelerometer unit had no problems during the testing phase.

*4.5.1.2 Turns*

Only the Gyro-Accelerometer unit placed under the seat was used to record the turns. The sensor was very effective in detecting the turns. The gyroscope only missed one of the 30° turns from testing conducted from a stop position (11 out of 12), while detecting all the turns in the moving case (12 out of 12). It also detected all the turns during the indoor and outdoor testing. The one turn that was missed during the testing from a stopped position, fell just 0.5° short of the 30° threshold as it was recorded as a 29.5° turn. A sample set of data is shown in Figure 21 for a moving-turn test; the graph shows that the turns cross the threshold 11 times during the moving-turn test, 6 times around the 30° mark and another 5 times over the 80° mark indicating the U-turns. Complete set of graphs can be seen in Appendix I.

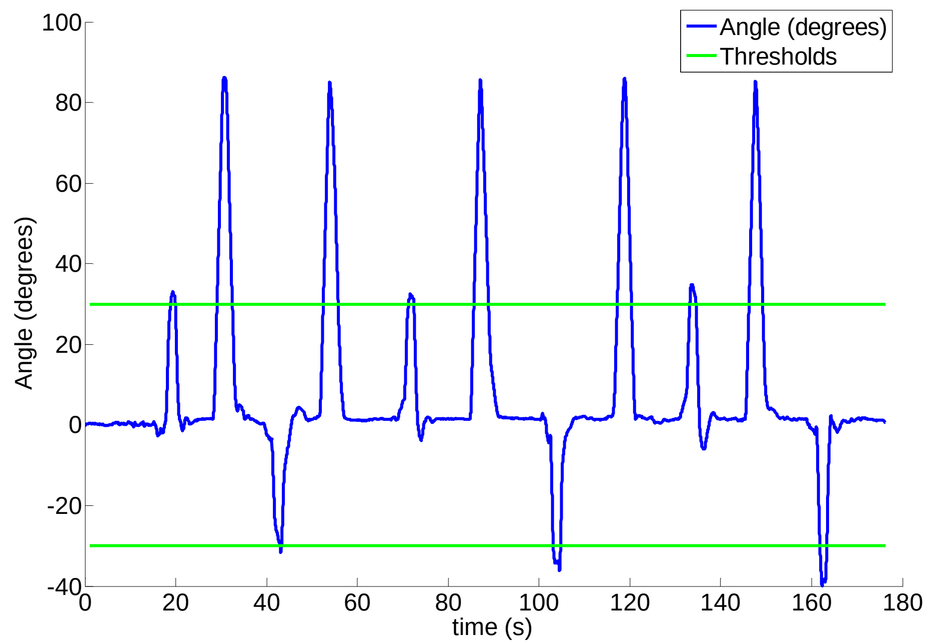



**Figure 21: Integrated turn angle over 2 second windows during a moving-turn test**

#### *4.5.1.3 Stops*

Stops were defined as non-motion of the wheels for a period of 2 seconds or more. The accelerometer on the rim was effective in picking up all the stops that were 2 seconds or greater in length, while seven out the ten 1s stops were detected. One problem that was recorded during the indoor testing was that the vibrations caused by transfer and weight shifts from one of the trials crossed the stop threshold. However, during that trial the wheels were not locked and the wheels rotated half a revolution. A sample data set from indoor testing is shown in Figure 22, while the complete set of data is posted in Appendix J.

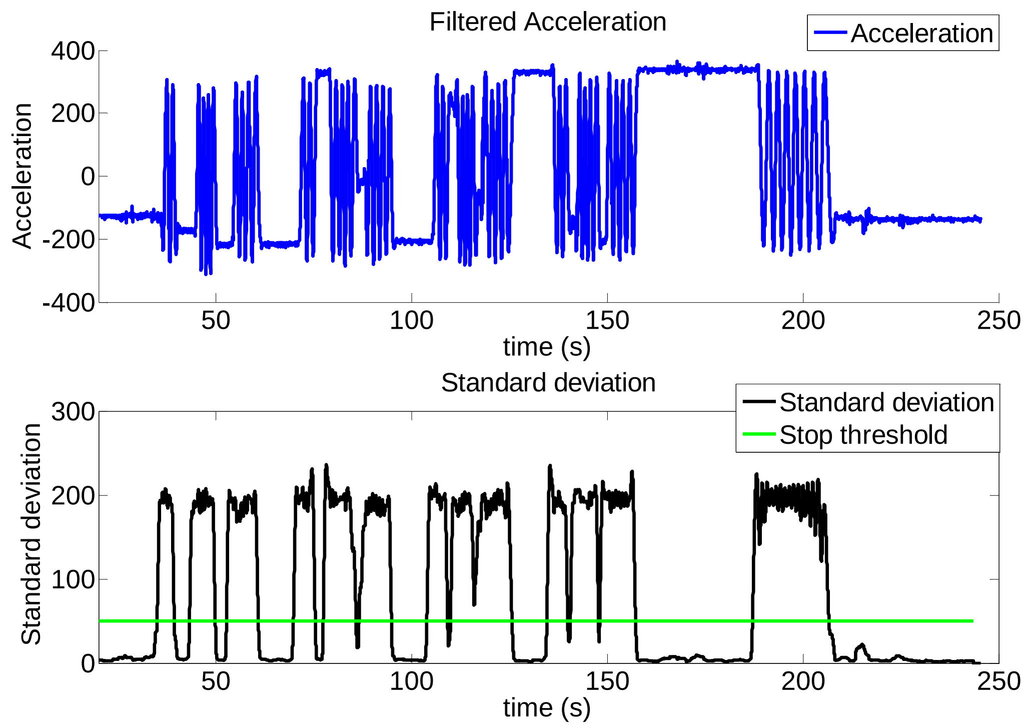



**Figure 22: Standard deviation profile used to detect stops along with filtered acceleration data**

The resolution for the reed switches was not sharp enough to pick up the 2 second stops effectively, as time between when the magnets crossed the switch was as high as 1.5-2 seconds during slow movements and as low as 0.5 seconds during faster propulsion. Therefore, the accuracy of the switches was limited to stops of 3 seconds or greater. However, if the number of magnets was doubled, the resolution would be high enough to detect 2 seconds stops.

Lastly, the data gathered from the accelerometer on the frame had similar profiles for movements when compared to weight shifts. Therefore, this unit could not be used to differentiate between starts, stops, and passengers shifting their weight.

#### 4.5.1.4 *Everyday mobility*

No unexpected results were obtained from the everyday mobility testing of power wheelchair users. The results for larger bouts of mobility corroborated with the self-reported times for the respective bouts, as well as time periods when the wheelchair was not in use. A complete set of bouts for the two users that were tested can be seen in Appendix K.

### 4.5.2 Compatibility and Battery Life

There are enough locations in both power and manual wheelchairs to attach a frame mounted units like the gyro-accelerometer unit. Therefore, the major concern for compatibility of the instrumentations was related to units that had to be attached to the wheel (reed switches and accelerometer on the rim). The accelerometer unit for the rim was thin enough to be attached to the outer face of a drive wheel hub using hot glue and tape for power wheelchairs tested without extending the profile. Moreover, the unit could be attached to the spokes of manual wheelchairs with zip-ties and a small amount of glue for added stability. The electronic boards were protected from outside elements by attaching a 3.2 mm plastic plate on one side and 1.59 mm plastic plate on the other side with hot glue. This resulted in a final dimension of (79 mm L, 44.5mm W and 12.7mm H) for the data logger and (28.6 mm L, 28.6mm W and 12.7 mm H) for the accelerometer shown in Figure 23.

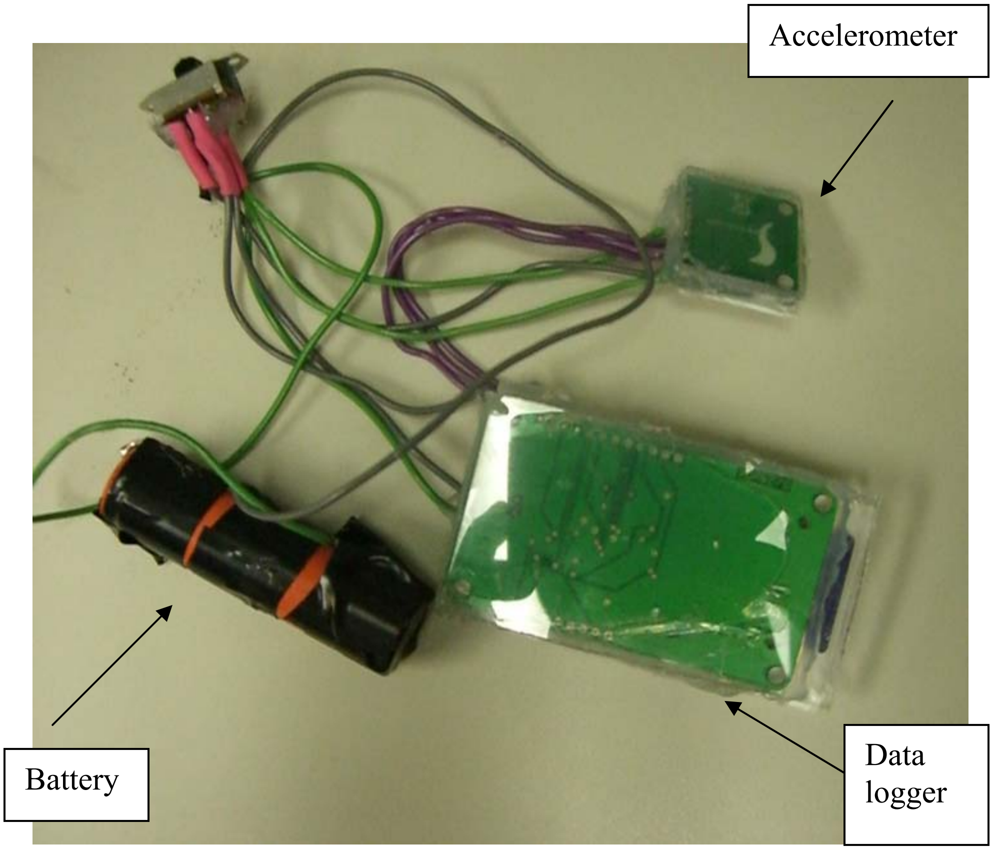



**Figure 23: Accelerometer unit for the rim**

Compatibility test for reed switches was not conducted, as extensive studies have been conducted in the past at CATEA that have used reed switches. Multiple problems have been reported in the past, with most common concern being, access to the inward facing side of the wheel to attach a magnet and aligning of the reed switch and the magnets.

The accelerometer-gyroscope unit and the reed switches can interface with the Levo science monitor currently in use for measuring everyday mobility, while the accelerometer on the rim requires the data logger used in this study or a similar sized logger. Since the accelerometer unit on the rim uses a separate data logger, synchronizing the data between the different loggers can be difficult.

The battery life of all the instrumentation was highly dependent on the data logger. As shown in Table 20 the reed switches and tri-axial accelerometer each required less than 1 milliamp of current while the gyroscope required 6 milliamps. However, the power consumption of the data logger was an order of magnitude higher at 80 milliamps, thus being the deciding factor in the overall battery life.

**Table 20: Current consumption of different components**

| **Component** | **Current Requirement** |
|---|---|
| Reed- Switch | 0.5 mA |
| Accelerometer | 0.5 mA |
| Gyroscope | 6 mA |
| Data Logger | 80 mA |

The batteries used for the accelerometer unit during this study were size ‘AA’ rechargeable Li-ion batteries with a capacity of 2600 mAh leading to a test time of approximately 30 hours. While four rechargeable nickel-metal hydride batteries with a capacity of 2700 mAh were used to for the gyro-accelerometer unit and the reed switches providing a battery life of approximately 24 hours. However, significantly higher capacity non-rechargeable batteries were available that were slightly bigger in overall dimensions. Primary lithium thionyl chloride batteries can provide 9 to 19Ah for a size ‘C’ and ‘D’ battery respectively, resulting in a battery life of 4-10 days. A complete list of recommended battery types are listed below in Table 21.

**Table 21: Recommended battery types**

| **Battery Type** | **Size** | **Capacity** | **Voltage** |
|---|---|---|---|
| Li-Ion ‘18650’ cylindrical cell (rechargeable) | ‘AA’ 18.3 mm (dia.) x 64.9 mm (H) | 2600 mAh | 3.6 V |
| Thionyl chloride (non-rechargeable) | ‘AA’ 14.55 mm (dia.) x 50.5 mm (H) | 2400 mAh | 3.6 V |
| Thionyl chloride (non-rechargeable) | ‘C’ 26.2 mm (dia.) x 50.5 mm (H) | 9Ah | 3.6 V |
| Thionyl chloride (non-rechargeable) | ‘D’ 34.2 mm (dia.) x 61.5 mm (H) | 19 Ah | 3.6 V |
| Polymer Li-Ion cell (rechargeable) | 100 mm (L) x 67 mm (W) x 5.7 mm (H) | 4250 mAh | 3.6 V |
| Polymer Li-Ion cell (rechargeable) | 85 mm (L) x 55 mm (W) x 6.4 mm (H) | 3200 mAh | 3.6 V |
| Nickel-Metal hydride (rechargeable) | ‘AA’ 17 mm (dia.) x 50 mm (H) | 2700 mAh | 1.2 V |
| Nickel-Metal hydride (rechargeable) | ‘4/3 AF’ 18 mm (dia.) x 67 mm (H) | 4500 mAh | 1.2 V |

## 4.6 Discussion

The major drawback of using the instrumentation suggested in this study is that, not all defined aspects of mobility can be measured using just one instrumentation method. The accelerometer unit on the rim and reed switches can measure starts, stops and distance, while only the gyroscope unit can measure turns. The problems with measuring turns using reed switches or accelerometer on the rim are discussed in section 4.6.2. Therefore two units have to be used in conjunction to achieve the measurement goals set by this study. Further discussion is broken up according to different aspects of design the criteria.

### 4.6.1 Starts, Stops and Distance

The reed-switches and accelerometer on the rim had similar accuracy levels for measuring distance, while the accelerometer unit was more effective at detecting stops. Then again, the number of magnets could be increased to improve the resolution of the reed switches, thereby allowing them to detect shorter duration stops. However, increasing the number of magnets would increase the set-up time and complexity, as all of the magnets have to be aligned with the reed switch. As a result, the accelerometer on the rim proved to be a better option for measuring these criteria.

### 4.6.2 Turns

The gyroscope mounted on the frame was the only unit that achieved the target set in the design criterion for measuring turns. Although the reed switches or accelerometer on the rim could be used to detect turn, it would greatly increase the complexity of the instrumentation and data analysis. A 90° turn on a manual wheelchair is an extra half a revolution of one wheel over the other wheel, requiring 4 magnets to effectively detect turns. Therefore, for a 30° turn would require 12 magnets to be attached to the wheel, thus greatly increasing the set-up time. Furthermore a hall-effect sensor would have to be used instead of a reed switch so that the direction of rotation of the wheel could be determined as well.

While for the accelerometer on the rim a much more complex algorithm would have to be developed that could break the data which looks like a sine wave into 12 different sections. However, there are two major problems, the frequency of the signal changes according to the rotational speed of the wheel, and the low signal to noise ratio when taking into account the desired accuracy level. Furthermore, implementing a complex algorithm would greatly increase the post-processing time as over 5 million data points are collected per day.

### 4.6.3 Everyday Mobility

The Accelerometer unit on the rim and the gyroscope on the frame performed well during everyday mobility testing. The results agreed with the bouts reported by the user. However, since data was gathered at 60 Hz, it resulted in 5.2 million data points per day. Therefore, a more efficient algorithm had to be developed to process the data.

Although, the new algorithm could process a day's data in less than 2 mins, data from multiple days would have to be broken up into single days since the computer would run of memory while processing larger sets of data.

### 4.6.4 Compatibility and Battery Life

Compatibility was not really an issue for the frame mounted accelerometer-gyro unit as there are several locations on the frame of a wheelchair where that unit could be attached. While, on the other hand, compatibility was a major concern at the start of the study for units that had to interface with the wheel. The accelerometer unit on the rim required a shorter attachment time when compared to reed switches as it was a stand alone unit. While on the other hand, the reed switches had to be aligned with the magnets. The accelerometer unit could be attached to the outer face of the wheel for most power wheelchairs, while access to the inner facing side of the wheel was required for reed switches, thus increasing complexity and set up time. Furthermore, the distance between the frame and wheels on a manual wheelchair is larger when compared to power wheelchairs, thus making it harder to maintain the distance between the magnets and reed switches to under 12.5mm.

The overall size of the accelerometer unit still needs to be reduced to improve the ease of attachment. The accelerometer and data logger could be combined into a single board, reducing the number of wires and the overall size. If these improvements are implemented, then the accelerometer unit would prove to be a significantly easier method to implement in order to measure starts, stops and distance when compared to the reed switches.

The battery life of the instrumentations is highly dependant on the data logger, as the logger power consumption is an order of magnitude higher than the sensors. Hence, a more efficient data logger will greatly improve the battery life of the instrumentations. The frequency of measurement did not have any effect on the power consumption for this data logger, even though it was running at 1/10 its capacity the power consumption only dropped by 3-4 milliamps. This implies that the majority of power was consumed in processing the data and not in writing the data to the SD card, which can be verified from the data sheet of the SD card writer; writing to the SD card requires 5 milliamps. If a more efficient microcontroller is used, similar to the Levo Science monitor used in an earlier study conducted at CATEA, then the power consumption could be reduced to as low as 5-10 milliamps for the data logger. The monitor uses Texas instruments' MSP430 family of microcontroller that requires only 280 microamps during active operation.

### 4.7 Conclusion

Overall the accelerometer unit on the rim proved to be a better option when compared to the reed switches for measuring starts, stops and distance. The accelerometer unit provided a better resolution and ease of attachment. Furthermore, by combining the data logger and accelerometer into a single unit the overall dimension and battery life of the unit could be improved, thus making it a significantly better option. Although the gyro-accelerometer unit on the frame achieved only one of the targets set out for the unit, it was not only very effective in measuring turns but also the only viable option from the sensors discussed in this study for measuring turns.

# CHAPTER 5

# CONCLUSION AND FUTURE WORK

This thesis looked into two aspects of wheeled mobility 1) The impact of a new tire design and, 2) Development of instrumentation to measure everyday mobility. The studies were conducted in that chronological order as simulated test results gathered from the Tweel™ technology tires study showed potential adverse health effects to users in the long run. However, there was not enough data available from everyday mobility to determine the extent of risks posed to the average wheelchair user. Therefore the second part of this thesis looked at various instrumentations that could be used to record different aspects of everyday wheeled mobility.

## 5.1 Tweel™ Technology Tires

Tweel™ technology tires failed to provide the level of performance that was expected from them. Before the tests were conducted improvement in ride comfort was considered as the biggest advantage of these tires over the solid foam-core tires commonly used by wheelchair users. The Tweel™ technology tires have deflection properties similar to pneumatic tires therefore the belief was that it would help dampen out the vibration transmitted to the wheelchair. However, the Tweel™ technology tires failed to produce any significant difference in the accelerations measured at the wheelchair seat.

Although the Tweel™ technology tires did provide better traction under both wet and dry conditions, the expected life span was significantly lower than the current wheelchair tire standards. There was significant deterioration in the tread of the drive wheels which provide traction for the wheelchair, thus any initial advantage would be lost. Overall the Tweel™ technology tires have to be re-engineered to provide better damping properties, leading to lower vibrational levels transmitted to the user. Furthermore, the tire's life span has to be improved significantly before these tires become a viable option.

One major change that would help improve the Tweel™ drive wheels would be to change the rubber tread on them. The rubber tread used on the Tweel™ drive wheels consists of a harder compound than the standard foam-core tires. Thus, more of the higher frequency vibrations are transmitted by the Tweel™ drive wheels; noted during subjective testing. Changing this rubber tread would also help improve the life span of the tires as the tread showed significant signs of deterioration at the end of the field study. Lastly, the composition of the polyurethane needs to be changed to ensure that the fins on the Tweel™ technology tires do not cross their elastic limit.

A striking result that was derived from this study was the level of health risk posed to a wheelchair user from whole-body vibration exposure during everyday mobility. It showed that the vibration levels for an average user was within the caution zone set by the ISO standard 2631-1, which means that there is an elevated risk of health impairment. Additionally in terms of perceived comfort the level is above the 'Uncomfortable' range for most surfaces, suggesting work needs to be done to improve the overall ride comfort of the users and prevent detrimental effects from long term use.

Users can determine their individualized risk using ISO 2631-1 and the data generated within this study.

## 5.2 Mobility Instrumentation

The instrumentations discussed in this thesis provide some viable options for measuring different aspects of everyday mobility. Although no single unit can measure all desired aspects of mobility set out by this study, a combination of two sensors can achieve the desired result. The gyro-accelerometer unit attached to the frame can measure turns very effectively and meets all the other design criteria, while the accelerometer on the rim or reed switches can measure start, stops and distance.

Overall the accelerometer on the rim proved to be a better option when compared to the reed switches for measuring starts, stops and distance. The accelerometer unit provided similar resolution and was easier to install. Additionally, if the algorithm for calculating distance is improved, so that it counts 4+ times a revolution instead of 2 times a much higher resolution would be achieved for measuring distance. Furthermore, the data logger and accelerometer could be combined into a single unit, thus reducing the overall dimension as well as the number of external wires. Since, there would be no need for external ports on the data logger the combined unit would be approximately the size of the original data logger, or smaller if microSD cards are used instead of standard SD card. Lastly, the battery life of the unit could be improved by changing the microcontroller to a more efficient one, thus making the accelerometer unit a significantly better option than the reed switches.

### 5.3 Future Work

Although this thesis brought forward an important potential health hazard faced by user from vibration exposure during everyday mobility, the methodology had several limitations. Tests were conducted by a single user on a wheelchair without a suspension system, and the damping from the cushion was ignored via sensor placement. Future studies need to conducted that take into account the damping provided by the cushion as that would be the true measure of the whole-body vibration transmitted to the user. Moreover, different types of wheelchairs could be tested, some with suspension systems, as this would not only help users determine their individualized level of risk but it would also help them make an educated decision when selecting their wheelchairs.

Relating results from simulated environments similar to the ones conducted in this study to everyday usage is challenging, as there is a lack of information available about important aspects of wheeled mobility. Several instrumentation methods were discussed in this thesis that would help gather data from everyday usage. Nonetheless, work still needs to be done in order to improve the battery life of the sensors and reduce the overall dimension to improve compatibility and ease of attachment. Bluetooth capabilities could also be added to the accelerometer unit on the rim, thus adding the capability of communicating with other loggers, which would ease the synchronizing process. Furthermore, data could be downloaded onto a remote server on a daily basis allowing for quicker turn around time when interviewing subjects.

# APPENDIX A

## SURFACES PICTURES

**Figure 24: Smooth Concrete**

**Figure 25: Rough Concrete**

**Figure 26: Grass**

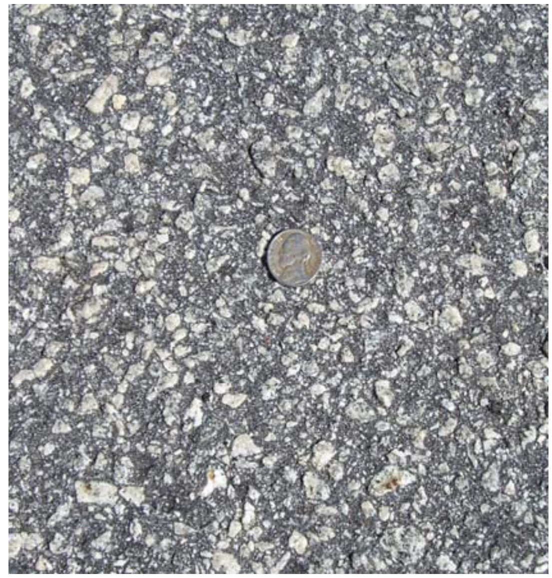


**Figure 27: Asphalt**

**Figure 28: Gravel**

# APPENDIX B

# MATLAB CODE

```
Y= importdata('filenames.txt');

Z = importdata('filesshort.txt');

diff_test = length(Z);

fs = 1024; % sampling freqency

% weighting and filtering tf from ISO

w1 = 2*pi*.4;
w2 = 2*pi*100;

Hh = tf([1 0 0],[1 sqrt(2)*w1 w1^2]);
Hl = tf ([1],[1/w2^2 sqrt(2)/w2 1]);

bp = Hh*Hl;    %%band pass filter

%% weighting filters
w3x = 2*pi*2;
w4x = 2*pi*2;

w3z = 2*pi*12.5;
w4z = 2*pi*12.5;

w5= 2*pi*2.37;
Q5 = .91;
w6= 2*pi*3.35;
Q6 = .91;

 Htz = tf([1/w3z 1],[1/w4z^2 1/(.63*w4z) 1]);
 Htx = tf([1/w3x 1],[1/w4x^2 1/(.63*w4x) 1]);
 Hsz = tf([1/w5^2 1/(Q5*w5) 1],[1/w6^2 1/(Q6*w5) 1]) ;

 Hw = Htz*Hsz*(w5/w6)^2;

ftz = bp*Hw;         %%%final filter z
ftx = bp*Htx;        %%%final filter x and y


%%loading all the files and running analysis

for a=1:13
   a
for w= 1:2
    pointer = strmatch(Z{a+(w-1)*13}, Y);
    diff = length(pointer);      %% checks for number of runs
```

```
clear X n E AA f sq rms fsn rms Xf W meanval
j=1;
for j=1:diff
X = dlmread(Y{pointer(j)},'\t',1,0);    %%load run
n = length(X);
fs = 1024;   %sampling rate

f = (0:n-1)*fs/(n-1); %freq vector

t= (0:1/1024:(n-1)/1024);   %%time vector

%% running the data through filters

%%% 2=x , 3=y 4=z of sensor under the seat
%%% 6=x , 7=y 8=z of bite-bar sensor

W(:,1) = lsim(ftx,X(:,2),t);
W(:,2) = lsim(ftx,X(:,3),t);
W(:,3) = lsim(ftz,X(:,4),t);

W(:,4) = lsim(ftx,X(:,6),t);
W(:,5) = lsim(ftx,X(:,7),t);
W(:,6) = lsim(ftz,X(:,8),t);


%%%run the fft



E(:,1) = fft(W(:,1),n);
E(:,2) = fft(W(:,2),n);
E(:,3) = fft(W(:,3),n);
E(:,4) = fft(W(:,4),n);
E(:,5) = fft(W(:,5),n);
E(:,6) = fft(W(:,6),n);

AA = abs(E);



sq = (AA.^2)/n;

%%center freq values from ISO
cf = [1.0 1.25 1.6 2.0 2.5 3.15 4.0 5.0 6.3 8.0 10.0 12.5 16 20 25 31.5
40 50 63 80];

diff_f = length(cf);

%%% taking the mean of the 3rd octaves
for k =1:6
 for m=1:diff_f

   rdoct = round(n/fs*0.13*cf(m));
   center = round(cf(m)*n/fs);
```

```
   mean_third(m) = mean(sq(center-rdoct:center+rdoct,k));

 end

meanval(k) = mean(mean_third(1:m));

end


%%% storing RMS values in a matrix
if (w ==1)
    RMSX1_s(a,j) = sqrt(meanval(1));
    RMSY1_s(a,j) = sqrt(meanval(2));
    RMSZ1_s(a,j) = sqrt(meanval(3));

    RMSX2_s(a,j) = sqrt(meanval(4));
    RMSY2_s(a,j) = sqrt(meanval(5));
    RMSZ2_s(a,j) = sqrt(meanval(6));

else
    RMSX1_t(a,j) = sqrt(meanval(1));
    RMSY1_t(a,j) = sqrt(meanval(2));
    RMSZ1_t(a,j) = sqrt(meanval(3));

    RMSX2_t(a,j) = sqrt(meanval(4));
    RMSY2_t(a,j) = sqrt(meanval(5));
    RMSZ2_t(a,j) = sqrt(meanval(6));


end




end

end



end

%%select the kx and ky values according to health or comfort
%% health effects
%%kx = 1.4;
%%ky = 1.4;

%%Comfort
%%kx = 1;
%%ky = 1;
```

```
kx = 1.4;
ky = 1.4;

    %%weighted RSS used to ISO comparison
    %%standard tires
    RSS_s1 = sqrt(RMSX1_s.^2*kx + RMSY1_s.^2*ky + RMSZ1_s.^2);
    RSS_s2 = sqrt(RMSX2_s.^2*kx + RMSY2_s.^2*ky + RMSZ2_s.^2);
    %% Tweel tires
    RSS_t1 = sqrt(RMSX1_t.^2*kx + RMSY1_t.^2*kx + RMSZ1_t.^2);
    RSS_t2 = sqrt(RMSX2_t.^2*kx + RMSY2_t.^2*kx + RMSZ2_t.^2);
```

## APPENDIX C

## RMS VALUES FOR HEALTH EFFECTS AND PERCEIVED COMFORT

**Table 22: Health effect RMS values at 1m/s (Z-direction only)**

| | Standard Tires | | | |
|---|---|---|---|---|
| Asphalt (1) | 2.0034 | 1.9564 | 2.0258 | 2.0376 |
| Rough Concrete (2) | 0.5371 | 0.4745 | 0.4804 | 0.4589 |
| Smooth Concrete (3) | 0.4205 | 0.3701 | 0.4295 | 0.3984 |
| Grass (4) | 1.9412 | 2.0931 | 2.2292 | 2.1339 |
| Gravel (5) | 4.5515 | 4.9949 | 4.4974 | 4.9221 |
| Obstacles run with riser (6) | 3.5368 | 3.6296 | 3.5237 | 3.6728 |
| Obstacles run with step-down (7) | 3.6522 | 3.6375 | 3.5416 | 3.6738 |
| Obstacle run with potholes (8) | 4.2667 | 4.201 | 4.1857 | 4.1673 |
| | Tweel™s | | | |
| Asphalt (1) | 2.5298 | 2.3841 | 2.4084 | 2.2732 |
| Rough Concrete (2) | 0.6169 | 0.6379 | 0.6524 | 0.6418 |
| Smooth Concrete (3) | 0.5017 | 0.5193 | 0.4722 | 0.5239 |
| Grass (4) | 1.6756 | 1.8219 | 1.8206 | 1.7495 |
| Gravel (5) | 4.7132 | 4.945 | 5.2294 | 4.6287 |
| Obstacles run with riser (6) | 3.5075 | 3.5849 | 3.9345 | 3.8377 |
| Obstacles run with step-down (7) | 3.8883 | 3.8774 | 3.7625 | 3.9811 |
| Obstacle run with potholes (8) | 4.1275 | 4.1216 | 4.13 | 4.146 |

**Table 23: Health effects RMS values at 1.5m/s (Z- direction only)**

| | Standard Tires | | | |
|---|---|---|---|---|
| Asphalt (1) | 2.5301 | 2.4694 | 2.6348 | 2.3902 |
| Rough Concrete (2) | 0.8199 | 0.6992 | 0.8001 | 0.823 |
| Smooth Concrete (3) | 0.712 | 0.6562 | 0.67 | 0.6848 |
| Grass (4) | 3.0874 | 2.999 | 3.1713 | 3.0334 |
| Gravel (5) | 6.5444 | 7.0489 | 6.3762 | 6.7035 |
| | Tweel™s | | | |
| Asphalt (1) | 2.6542 | 2.4793 | 2.4493 | 2.5512 |
| Rough Concrete (2) | 0.7599 | 0.788 | 0.7208 | 0.7979 |
| Smooth Concrete (3) | 0.6371 | 0.6153 | 0.6471 | 0.6633 |
| Grass (4) | 2.8776 | 2.8668 | 2.7871 | 2.861 |
| Gravel (5) | 6.8543 | 6.811 | 5.6517 | 6.3903 |

**Table 24: Perceived comfort RMS values at 1m/s**

| | Standard Tires | | | |
|---|---|---|---|---|
| Asphalt (1) | 2.1565 | 2.0718 | 2.1784 | 2.169 |
| Rough Concrete (2) | 0.8058 | 0.6805 | 0.7177 | 0.6528 |
| Smooth Concrete (3) | 0.6655 | 0.6489 | 0.7011 | 0.6743 |
| Grass (4) | 2.5334 | 2.4584 | 2.6486 | 2.5315 |
| Gravel (5) | 4.8261 | 5.3091 | 4.7055 | 5.1975 |
| Obstacles run with riser (6) | 3.9298 | 4.0448 | 3.9716 | 4.0358 |
| Obstacles run with step-down (7) | 3.9271 | 3.9881 | 3.7813 | 3.9669 |
| Obstacle run with potholes (8) | 4.7717 | 4.7099 | 4.7455 | 4.7825 |
| | **Tweel™s** | | | |
| Asphalt (1) | 2.6715 | 2.5333 | 2.5948 | 2.4598 |
| Rough Concrete (2) | 0.8911 | 0.8716 | 0.9674 | 0.8517 |
| Smooth Concrete (3) | 0.8527 | 0.8692 | 0.9016 | 0.8898 |
| Grass (4) | 2.1386 | 2.2668 | 2.443 | 2.1981 |
| Gravel (5) | 4.9757 | 5.2103 | 5.4992 | 4.959 |
| Obstacles run with riser (6) | 3.9433 | 4.0044 | 4.2421 | 4.242 |
| Obstacles run with step-down (7) | 4.1603 | 4.1894 | 4.0951 | 4.2422 |
| Obstacle run with potholes (8) | 4.6191 | 4.5264 | 4.5875 | 4.5151 |

**Table 25: Perceived comfort RMS values at 1.5m/s**

| | Standard Tires | | | |
|---|---|---|---|---|
| Asphalt (1) | 2.8802 | 2.6563 | 2.91 | 2.5544 |
| Rough Concrete (2) | 1.5366 | 1.0572 | 1.5523 | 1.197 |
| Smooth Concrete (3) | 1.2917 | 1.5349 | 1.4841 | 1.3421 |
| Grass (4) | 3.7018 | 3.4988 | 3.7237 | 3.5426 |
| Gravel (5) | 6.8591 | 7.3381 | 6.5849 | 6.9392 |
| | **Tweel™s** | | | |
| Asphalt (1) | 2.9332 | 2.789 | 2.7349 | 2.907 |
| Rough Concrete (2) | 1.2146 | 1.1827 | 1.2947 | 1.0241 |
| Smooth Concrete (3) | 1.5024 | 1.3911 | 1.683 | 1.2531 |
| Grass (4) | 3.2688 | 3.259 | 3.211 | 3.348 |
| Gravel (5) | 7.1278 | 7.1116 | 5.9011 | 6.6414 |

# APPENDIX D

# ANOVA ANALYSIS FOR SURFACES

### Descriptive Statistics: Health

### Results for Wheel = 1

| Variable | Speed | Mean | StDev | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Health | 1 | 1.948 | 1.616 | 0.370 | 1.980 | 4.995 |
| | 2 | 2.743 | 2.235 | 0.656 | 2.500 | 7.049 |

### Results for Wheel = 2

| Variable | Speed | Mean | StDev | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Health | 1 | 2.037 | 1.632 | 0.472 | 1.785 | 5.229 |
| | 2 | 2.643 | 2.159 | 0.615 | 2.515 | 6.854 |

### Descriptive Statistics: Comfort

### Results for Wheel = 1

| Variable | Speed | Mean | StDev | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Comfort | 1 | 2.217 | 1.630 | 0.649 | 2.163 | 5.309 |
| | 2 | 3.209 | 2.109 | 1.057 | 2.768 | 7.338 |

### Results for Wheel = 2

| Variable | Speed | Mean | StDev | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Comfort | 1 | 2.352 | 1.610 | 0.852 | 2.232 | 5.499 |
| | 2 | 3.089 | 2.037 | 1.024 | 2.848 | 7.128 |

### General Linear Model: Health, Comfort versus Wheel, Speed, Surface

| Factor | Type | Levels | Values |
|---|---|---|---|
| Wheel | fixed | 2 | 1, 2 |
| Speed | fixed | 2 | 1, 2 |
| Surface | fixed | 5 | 1, 2, 3, 4, 5 |

Analysis of Variance for Health, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Wheel | 1 | 0.001 | 0.001 | 0.001 | 0.00 | 0.951 |
| Speed | 1 | 9.811 | 9.811 | 9.811 | 72.64 | 0.000 |
| Surface | 4 | 274.054 | 274.054 | 68.513 | 507.26 | 0.000 |
| Wheel*Speed | 1 | 0.179 | 0.179 | 0.179 | 1.32 | 0.254 |
| Wheel*Surface | 4 | 0.518 | 0.518 | 0.130 | 0.96 | 0.436 |
| Error | 68 | 9.184 | 9.184 | 0.135 | | |
| Total | 79 | 293.746 | | | | |

```
S = 0.367512   R-Sq = 96.87%   R-Sq(adj) = 96.37%


Unusual Observations for Health

Obs   Health      Fit   SE Fit  Residual  St Resid
 33  4.55150  5.30742  0.14234  -0.75592     -2.23 R
 35  4.49740  5.30742  0.14234  -0.81002     -2.39 R
 38  7.04890  6.10231  0.14234   0.94659      2.79 R
 76  4.62870  5.35001  0.14234  -0.72131     -2.13 R
 77  6.85430  5.95589  0.14234   0.89841      2.65 R
 78  6.81100  5.95589  0.14234   0.85511      2.52 R

R denotes an observation with a large standardized residual.


Analysis of Variance for Comfort, using Adjusted SS for Tests

Source         DF   Seq SS   Adj SS  Adj MS       F      P
Wheel           1    0.001    0.001   0.001    0.01  0.916
Speed           1   14.952   14.952  14.952  142.74  0.000
Surface         4  255.181  255.181  63.795  609.03  0.000
Wheel*Speed     1    0.328    0.328   0.328    3.13  0.081
Wheel*Surface   4    0.723    0.723   0.181    1.73  0.154
Error          68    7.123    7.123   0.105
Total          79  278.308


S = 0.323650   R-Sq = 97.44%   R-Sq(adj) = 97.03%


Unusual Observations for Comfort

Obs  Comfort      Fit   SE Fit  Residual  St Resid
 33  4.82610  5.47362  0.12535  -0.64752     -2.17 R
 35  4.70550  5.47362  0.12535  -0.76812     -2.57 R
 38  7.33810  6.46625  0.12535   0.87185      2.92 R
 76  4.95900  5.55993  0.12535  -0.60093     -2.01 R
 77  7.12780  6.29660  0.12535   0.83120      2.79 R
 78  7.11160  6.29660  0.12535   0.81500      2.73 R

R denotes an observation with a large standardized residual.



Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Surface
Surface = 1  subtracted from:

         Difference       SE of           Adjusted
Surface    of Means  Difference  T-Value   P-Value
2            -1.692      0.1299   -13.02    0.0000
3            -1.803      0.1299   -13.88    0.0000
4             0.086      0.1299     0.66    0.0242
5             3.318      0.1299    25.53    0.0000


Surface = 2  subtracted from:

         Difference       SE of           Adjusted
```

| Surface | of Means | Difference | T-Value | P-Value |
|---|---|---|---|---|
| 3 | -0.1117 | 0.1299 | -0.8597 | 0.9105 |
| 4 | 1.7775 | 0.1299 | 13.6798 | 0.0000 |
| 5 | 5.0096 | 0.1299 | 38.5547 | 0.0000 |

Surface = 3 subtracted from:

| Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 4 | 1.889 | 0.1299 | 14.54 | 0.0000 |
| 5 | 5.121 | 0.1299 | 39.41 | 0.0000 |

Surface = 4 subtracted from:

| Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 5 | 3.232 | 0.1299 | 24.87 | 0.0000 |

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Wheel*Surface
Wheel = 1
Surface = 1 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 2 | -1.619 | 0.1838 | -8.812 | 0.0000 |
| 1 | 3 | -1.713 | 0.1838 | -9.324 | 0.0000 |
| 1 | 4 | 0.330 | 0.1838 | 1.796 | 0.7351 |
| 1 | 5 | 3.449 | 0.1838 | 18.769 | 0.0000 |
| 2 | 1 | 0.210 | 0.1838 | 1.144 | 0.9780 |
| 2 | 2 | -1.554 | 0.1838 | -8.457 | 0.0000 |
| 2 | 3 | -1.683 | 0.1838 | -9.161 | 0.0000 |
| 2 | 4 | 0.052 | 0.1838 | 0.281 | 1.0000 |
| 2 | 5 | 3.397 | 0.1838 | 18.486 | 0.0000 |

Wheel = 1
Surface = 2 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 3 | -0.09395 | 0.1838 | -0.5113 | 1.0000 |
| 1 | 4 | 1.94943 | 0.1838 | 10.6088 | 0.0000 |
| 1 | 5 | 5.06823 | 0.1838 | 27.5812 | 0.0000 |
| 2 | 1 | 1.82955 | 0.1838 | 9.9564 | 0.0000 |
| 2 | 2 | 0.06531 | 0.1838 | 0.3554 | 1.0000 |
| 2 | 3 | -0.06415 | 0.1838 | -0.3491 | 1.0000 |
| 2 | 4 | 1.67088 | 0.1838 | 9.0929 | 0.0000 |
| 2 | 5 | 5.01631 | 0.1838 | 27.2987 | 0.0000 |

Wheel = 1
Surface = 3 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 4 | 2.04338 | 0.1838 | 11.1200 | 0.0000 |

| | | | | | |
|---|---|---|---|---|---|
| 1 | 5 | 5.16218 | 0.1838 | 28.0925 | 0.0000 |
| 2 | 1 | 1.92350 | 0.1838 | 10.4677 | 0.0000 |
| 2 | 2 | 0.15926 | 0.1838 | 0.8667 | 0.9970 |
| 2 | 3 | 0.02980 | 0.1838 | 0.1622 | 1.0000 |
| 2 | 4 | 1.76483 | 0.1838 | 9.6042 | 0.0000 |
| 2 | 5 | 5.11026 | 0.1838 | 27.8100 | 0.0000 |

Wheel = 1
Surface = 4 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 5 | 3.119 | 0.1838 | 16.97 | 0.0000 |
| 2 | 1 | -0.120 | 0.1838 | -0.65 | 0.9997 |
| 2 | 2 | -1.884 | 0.1838 | -10.25 | 0.0000 |
| 2 | 3 | -2.014 | 0.1838 | -10.96 | 0.0000 |
| 2 | 4 | -0.279 | 0.1838 | -1.52 | 0.8811 |
| 2 | 5 | 3.067 | 0.1838 | 16.69 | 0.0000 |

Wheel = 1
Surface = 5 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 1 | -3.239 | 0.1838 | -17.62 | 0.0000 |
| 2 | 2 | -5.003 | 0.1838 | -27.23 | 0.0000 |
| 2 | 3 | -5.132 | 0.1838 | -27.93 | 0.0000 |
| 2 | 4 | -3.397 | 0.1838 | -18.49 | 0.0000 |
| 2 | 5 | -0.052 | 0.1838 | -0.28 | 1.0000 |

Wheel = 2
Surface = 1 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 2 | -1.764 | 0.1838 | -9.60 | 0.0000 |
| 2 | 3 | -1.894 | 0.1838 | -10.31 | 0.0000 |
| 2 | 4 | -0.159 | 0.1838 | -0.86 | 0.9971 |
| 2 | 5 | 3.187 | 0.1838 | 17.34 | 0.0000 |

Wheel = 2
Surface = 2 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 3 | -0.1295 | 0.1838 | -0.7045 | 0.9994 |
| 2 | 4 | 1.6056 | 0.1838 | 8.7375 | 0.0000 |
| 2 | 5 | 4.9510 | 0.1838 | 26.9433 | 0.0000 |

Wheel = 2
Surface = 3 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 4 | 1.735 | 0.1838 | 9.442 | 0.0000 |
| 2 | 5 | 5.080 | 0.1838 | 27.648 | 0.0000 |

Wheel = 2
Surface = 4  subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 5 | 3.345 | 0.1838 | 18.21 | 0.0000 |

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Surface
Surface = 1  subtracted from:

| Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 2 | -1.544 | 0.1144 | -13.49 | 0.0000 |
| 3 | -1.470 | 0.1144 | -12.84 | 0.0000 |
| 4 | 0.348 | 0.1144 | 3.04 | 0.0266 |
| 5 | 3.374 | 0.1144 | 29.49 | 0.0000 |

Surface = 2  subtracted from:

| Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 3 | 0.07423 | 0.1144 | 0.6487 | 0.9663 |
| 4 | 1.89214 | 0.1144 | 16.5357 | 0.0000 |
| 5 | 4.91799 | 0.1144 | 42.9791 | 0.0000 |

Surface = 3  subtracted from:

| Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 4 | 1.818 | 0.1144 | 15.89 | 0.0000 |
| 5 | 4.844 | 0.1144 | 42.33 | 0.0000 |

Surface = 4  subtracted from:

| Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 5 | 3.026 | 0.1144 | 26.44 | 0.0000 |

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Wheel*Surface
Wheel = 1
Surface = 1  subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 2 | -1.422 | 0.1618 | -8.788 | 0.0000 |
| 1 | 3 | -1.404 | 0.1618 | -8.678 | 0.0000 |
| 1 | 4 | 0.633 | 0.1618 | 3.910 | 0.0077 |
| 1 | 5 | 3.523 | 0.1618 | 21.770 | 0.0000 |
| 2 | 1 | 0.256 | 0.1618 | 1.581 | 0.8525 |
| 2 | 2 | -1.410 | 0.1618 | -8.712 | 0.0000 |
| 2 | 3 | -1.279 | 0.1618 | -7.905 | 0.0000 |
| 2 | 4 | 0.320 | 0.1618 | 1.975 | 0.6190 |

| | | | | | |
|---|---|---|---|---|---|
| 2 | 5 | 3.481 | 0.1618 | 21.512 | 0.0000 |

Wheel = 1
Surface = 2 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 3 | 0.01784 | 0.1618 | 0.1102 | 1.0000 |
| 1 | 4 | 2.05486 | 0.1618 | 12.6981 | 0.0000 |
| 1 | 5 | 4.94495 | 0.1618 | 30.5574 | 0.0000 |
| 2 | 1 | 1.67795 | 0.1618 | 10.3689 | 0.0000 |
| 2 | 2 | 0.01225 | 0.1618 | 0.0757 | 1.0000 |
| 2 | 3 | 0.14288 | 0.1618 | 0.8829 | 0.9965 |
| 2 | 4 | 1.74168 | 0.1618 | 10.7627 | 0.0000 |
| 2 | 5 | 4.90328 | 0.1618 | 30.2999 | 0.0000 |

Wheel = 1
Surface = 3 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 4 | 2.03702 | 0.1618 | 12.5878 | 0.0000 |
| 1 | 5 | 4.92711 | 0.1618 | 30.4472 | 0.0000 |
| 2 | 1 | 1.66011 | 0.1618 | 10.2587 | 0.0000 |
| 2 | 2 | -0.00559 | 0.1618 | -0.0345 | 1.0000 |
| 2 | 3 | 0.12504 | 0.1618 | 0.7727 | 0.9988 |
| 2 | 4 | 1.72384 | 0.1618 | 10.6525 | 0.0000 |
| 2 | 5 | 4.88544 | 0.1618 | 30.1897 | 0.0000 |

Wheel = 1
Surface = 4 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 5 | 2.890 | 0.1618 | 17.86 | 0.0000 |
| 2 | 1 | -0.377 | 0.1618 | -2.33 | 0.3845 |
| 2 | 2 | -2.043 | 0.1618 | -12.62 | 0.0000 |
| 2 | 3 | -1.912 | 0.1618 | -11.82 | 0.0000 |
| 2 | 4 | -0.313 | 0.1618 | -1.94 | 0.6456 |
| 2 | 5 | 2.848 | 0.1618 | 17.60 | 0.0000 |

Wheel = 1
Surface = 5 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 1 | -3.267 | 0.1618 | -20.19 | 0.0000 |
| 2 | 2 | -4.933 | 0.1618 | -30.48 | 0.0000 |
| 2 | 3 | -4.802 | 0.1618 | -29.67 | 0.0000 |
| 2 | 4 | -3.203 | 0.1618 | -19.79 | 0.0000 |
| 2 | 5 | -0.042 | 0.1618 | -0.26 | 1.0000 |

Wheel = 2
Surface = 1 subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 2 | -1.666 | 0.1618 | -10.29 | 0.0000 |

| | | | | | |
|---|---|---|---|---|---|
| 2 | 3 | -1.535 | 0.1618 | -9.49 | 0.0000 |
| 2 | 4 | 0.064 | 0.1618 | 0.39 | 1.0000 |
| 2 | 5 | 3.225 | 0.1618 | 19.93 | 0.0000 |

Wheel = 2
Surface = 2  subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 3 | 0.1306 | 0.1618 | 0.8072 | 0.9982 |
| 2 | 4 | 1.7294 | 0.1618 | 10.6870 | 0.0000 |
| 2 | 5 | 4.8910 | 0.1618 | 30.2242 | 0.0000 |

Wheel = 2
Surface = 3  subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 4 | 1.599 | 0.1618 | 9.880 | 0.0000 |
| 2 | 5 | 4.760 | 0.1618 | 29.417 | 0.0000 |

Wheel = 2
Surface = 4  subtracted from:

| Wheel | Surface | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 5 | 3.162 | 0.1618 | 19.54 | 0.0000 |

# APPENDIX E

# ANOVA ANALYSIS FOR OBSTACLES

### Descriptive Statistics: Health

| Variable | Tires | Mean | StDev | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Health | 1 | 3.8074 | 0.2990 | 3.5237 | 3.6625 | 4.2667 |
| | 2 | 3.9083 | 0.2128 | 3.5075 | 3.9114 | 4.1460 |

### Descriptive Statistics: Comfort

| Variable | Tires | Mean | StDev | Minimum | Median | Maximum |
|---|---|---|---|---|---|---|
| Comfort | 1 | 4.221 | 0.398 | 3.781 | 4.012 | 4.783 |
| | 2 | 4.2806 | 0.2288 | 3.9433 | 4.2421 | 4.6191 |

### General Linear Model: Health, Comfort versus Tires, Obstacle

| Factor | Type | Levels | Values |
|---|---|---|---|
| Tires | fixed | 2 | 1, 2 |
| Obstacle | fixed | 3 | 6, 7, 8 |

Analysis of Variance for Health, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Tires | 1 | 0.06103 | 0.06103 | 0.06103 | 6.13 | 0.023 |
| Obstacle | 2 | 1.19491 | 1.19491 | 0.59745 | 60.04 | 0.000 |
| Tires*Obstacle | 2 | 0.10740 | 0.10740 | 0.05370 | 5.40 | 0.015 |
| Error | 18 | 0.17910 | 0.17910 | 0.00995 | | |
| Total | 23 | 1.54245 | | | | |

S = 0.0997509   R-Sq = 88.39%   R-Sq(adj) = 85.16%

Unusual Observations for Health

| Obs | Health | Fit | SE Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 13 | 3.50750 | 3.71615 | 0.04988 | -0.20865 | -2.42 R |
| 15 | 3.93450 | 3.71615 | 0.04988 | 0.21835 | 2.53 R |

R denotes an observation with a large standardized residual.

Analysis of Variance for Comfort, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Tires | 1 | 0.02112 | 0.02112 | 0.02112 | 2.91 | 0.105 |
| Obstacle | 2 | 1.98121 | 1.98121 | 0.99060 | 136.54 | 0.000 |
| Tires*Obstacle | 2 | 0.20763 | 0.20763 | 0.10381 | 14.31 | 0.000 |
| Error | 18 | 0.13059 | 0.13059 | 0.00725 | | |
| Total | 23 | 2.34054 | | | | |

S = 0.0851755   R-Sq = 94.42%   R-Sq(adj) = 92.87%

Unusual Observations for Comfort

| Obs | Comfort | Fit | SE Fit | Residual | St Resid |
|---|---|---|---|---|---|
| 13 | 3.94330 | 4.10795 | 0.04259 | -0.16465 | -2.23 R |

R denotes an observation with a large standardized residual.

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Obstacle
Obstacle = 6  subtracted from:

| Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 7 | 0.09836 | 0.04988 | 1.972 | 0.1479 |
| 8 | 0.51479 | 0.04988 | 10.321 | 0.0000 |

Obstacle = 7  subtracted from:

| Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 8 | 0.4164 | 0.04988 | 8.349 | 0.0000 |

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Tires*Obstacle
Tires = 1
Obstacle = 6  subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 7 | 0.03555 | 0.07053 | 0.5040 | 0.9954 |
| 1 | 8 | 0.61445 | 0.07053 | 8.7113 | 0.0000 |
| 2 | 6 | 0.12543 | 0.07053 | 1.7782 | 0.5025 |
| 2 | 7 | 0.28660 | 0.07053 | 4.0633 | 0.0081 |
| 2 | 8 | 0.54055 | 0.07053 | 7.6636 | 0.0000 |

Tires = 1
Obstacle = 7  subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 8 | 0.57890 | 0.07053 | 8.207 | 0.0000 |
| 2 | 6 | 0.08988 | 0.07053 | 1.274 | 0.7947 |
| 2 | 7 | 0.25105 | 0.07053 | 3.559 | 0.0232 |
| 2 | 8 | 0.50500 | 0.07053 | 7.160 | 0.0000 |

Tires = 1
Obstacle = 8  subtracted from:

Difference       SE of            Adjusted

| Tires | Obstacle | of Means | Difference | T-Value | P-Value |
|---|---|---|---|---|---|
| 2 | 6 | -0.4890 | 0.07053 | -6.933 | 0.0000 |
| 2 | 7 | -0.3278 | 0.07053 | -4.648 | 0.0023 |
| 2 | 8 | -0.0739 | 0.07053 | -1.048 | 0.8953 |

Tires = 2
Obstacle = 6  subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 7 | 0.1612 | 0.07053 | 2.285 | 0.2500 |
| 2 | 8 | 0.4151 | 0.07053 | 5.885 | 0.0002 |

Tires = 2
Obstacle = 7  subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 8 | 0.2539 | 0.07053 | 3.600 | 0.0213 |

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Obstacle
Obstacle = 6  subtracted from:

| Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 7 | -0.007925 | 0.04259 | -0.1861 | 0.9811 |
| 8 | 0.605487 | 0.04259 | 14.2174 | 0.0000 |

Obstacle = 7  subtracted from:

| Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|
| 8 | 0.6134 | 0.04259 | 14.40 | 0.0000 |

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Tires*Obstacle
Tires = 1
Obstacle = 6  subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 7 | -0.07965 | 0.06023 | -1.322 | 0.7694 |
| 1 | 8 | 0.75690 | 0.06023 | 12.567 | 0.0000 |
| 2 | 6 | 0.11245 | 0.06023 | 1.867 | 0.4516 |
| 2 | 7 | 0.17625 | 0.06023 | 2.926 | 0.0814 |
| 2 | 8 | 0.56652 | 0.06023 | 9.406 | 0.0000 |

Tires = 1
Obstacle = 7  subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 1 | 8 | 0.8365 | 0.06023 | 13.890 | 0.0000 |
| 2 | 6 | 0.1921 | 0.06023 | 3.190 | 0.0489 |
| 2 | 7 | 0.2559 | 0.06023 | 4.249 | 0.0055 |
| 2 | 8 | 0.6462 | 0.06023 | 10.729 | 0.0000 |

Tires = 1
Obstacle = 8 subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 6 | -0.6444 | 0.06023 | -10.70 | 0.0000 |
| 2 | 7 | -0.5806 | 0.06023 | -9.64 | 0.0000 |
| 2 | 8 | -0.1904 | 0.06023 | -3.16 | 0.0517 |

Tires = 2
Obstacle = 6 subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 7 | 0.06380 | 0.06023 | 1.059 | 0.8910 |
| 2 | 8 | 0.45408 | 0.06023 | 7.539 | 0.0000 |

Tires = 2
Obstacle = 7 subtracted from:

| Tires | Obstacle | Difference of Means | SE of Difference | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| 2 | 8 | 0.3903 | 0.06023 | 6.480 | 0.0001 |

# APPENDIX F

# TRACTION ANGLE CALCULATION GRAPHS

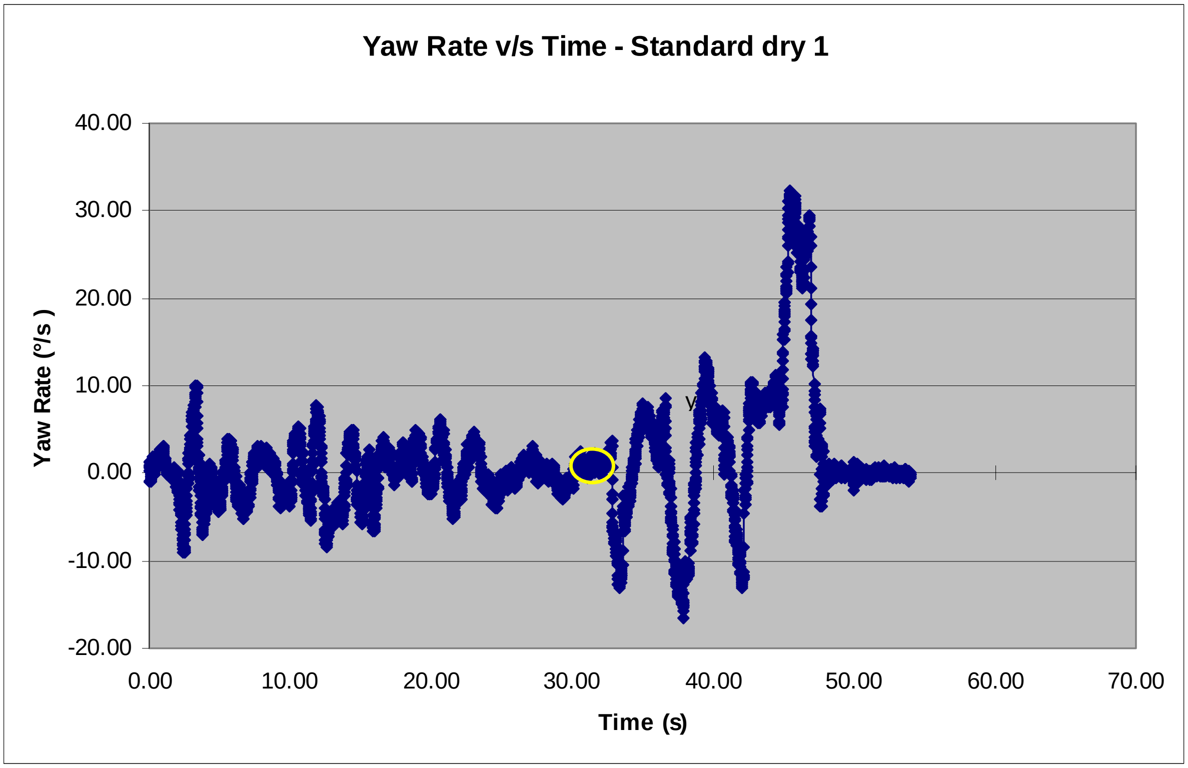



**Figure 29: Standard tires yaw rate v/s time dry condition test 1**

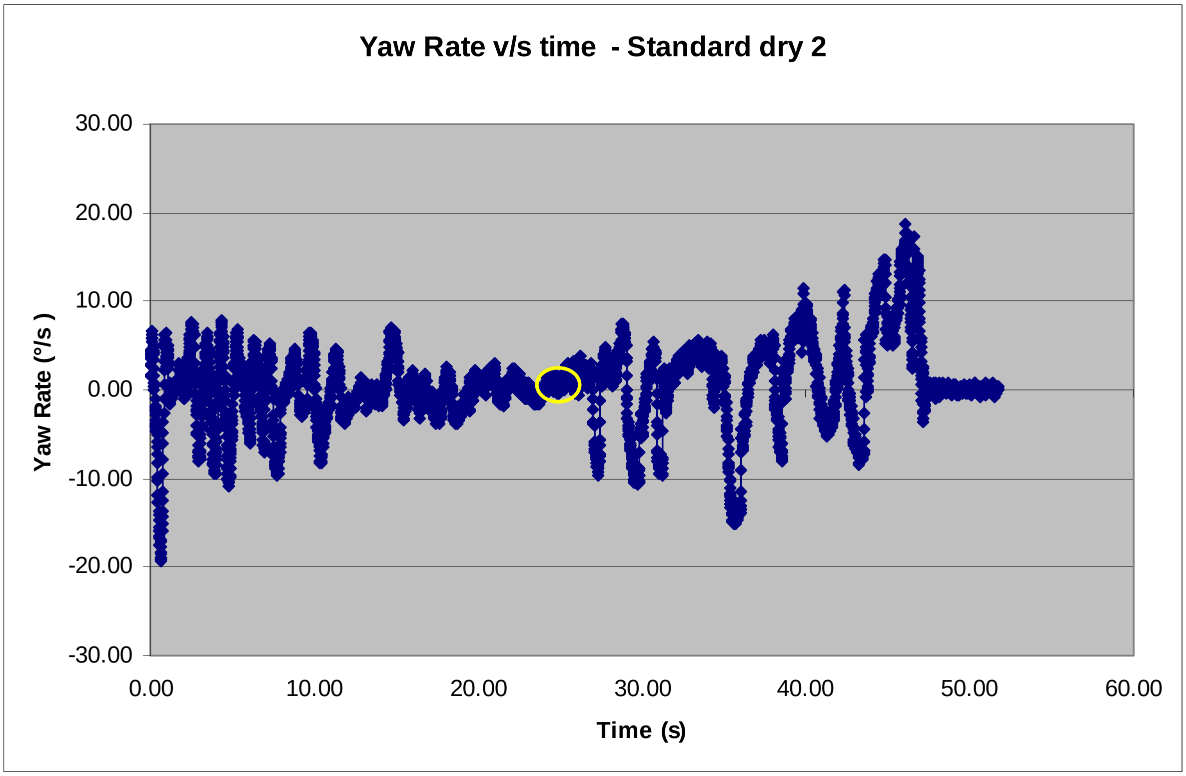



**Figure 30: Standard tires yaw rate v/s time dry condition test 2**

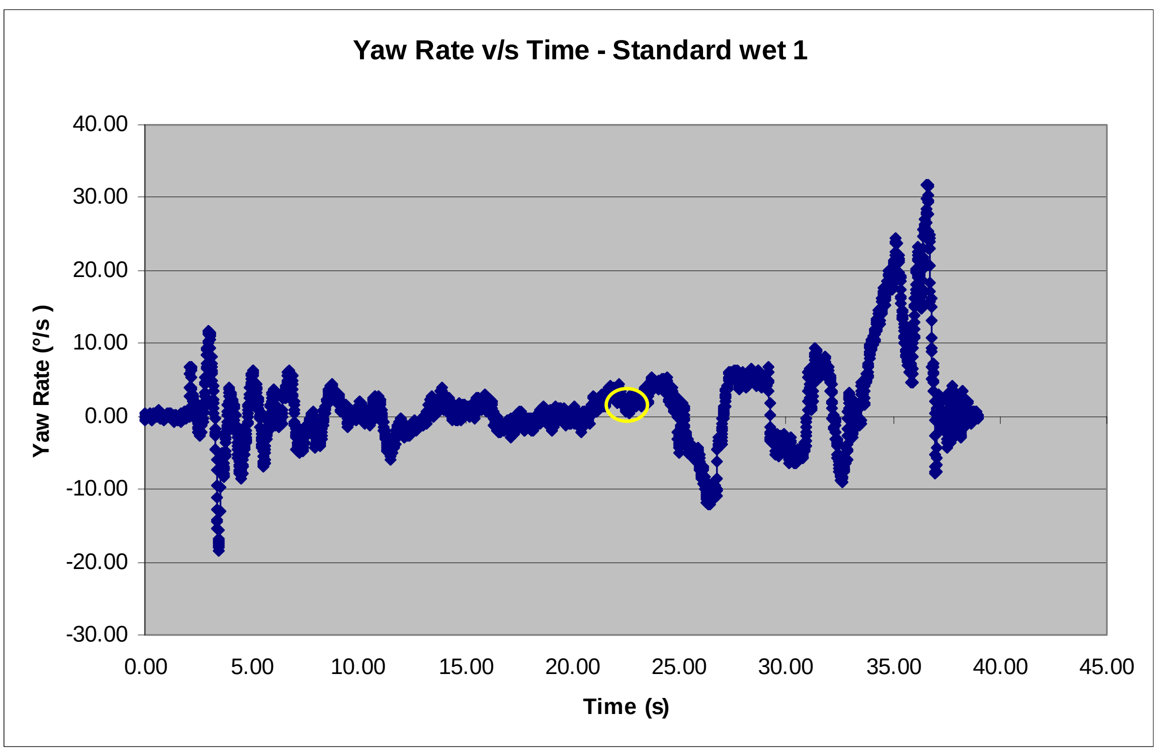



**Figure 31: Standard tires yaw rate v/s time wet condition test 1**

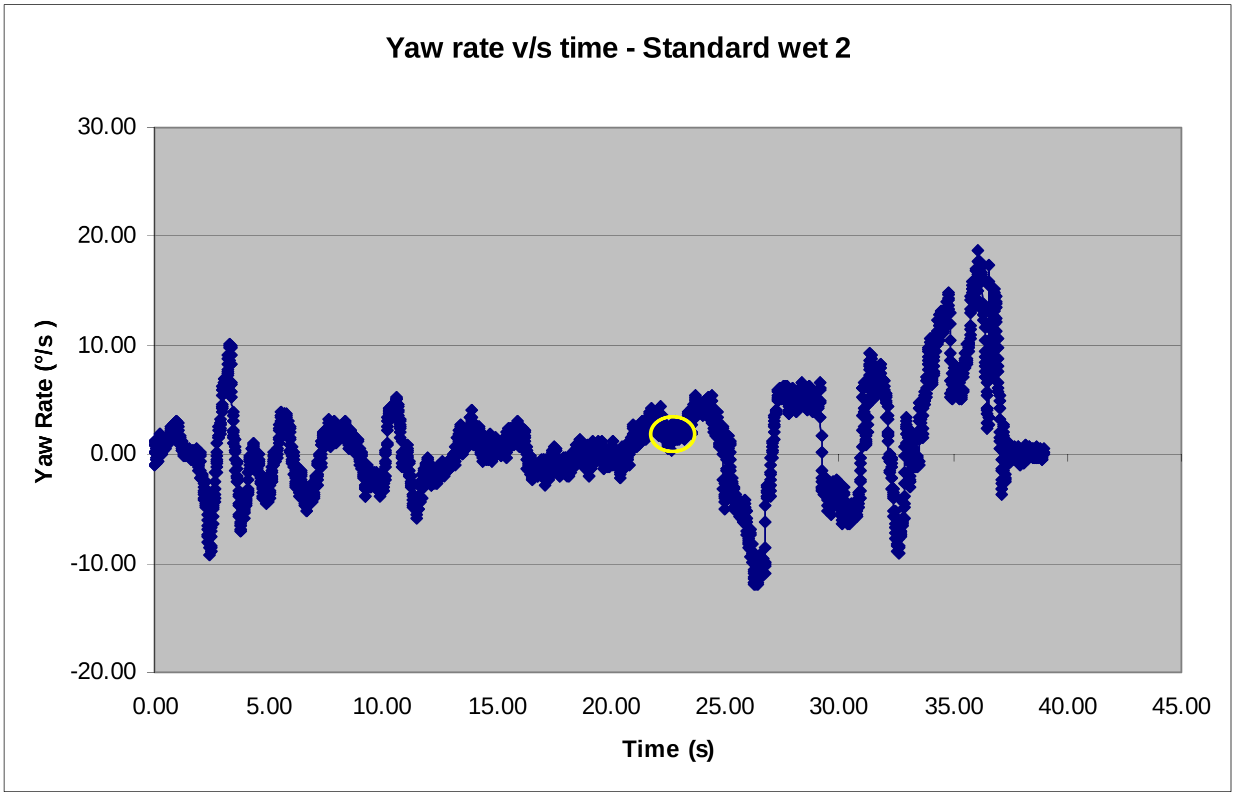



**Figure 32: Standard tires yaw rate v/s time wet condition test 2**

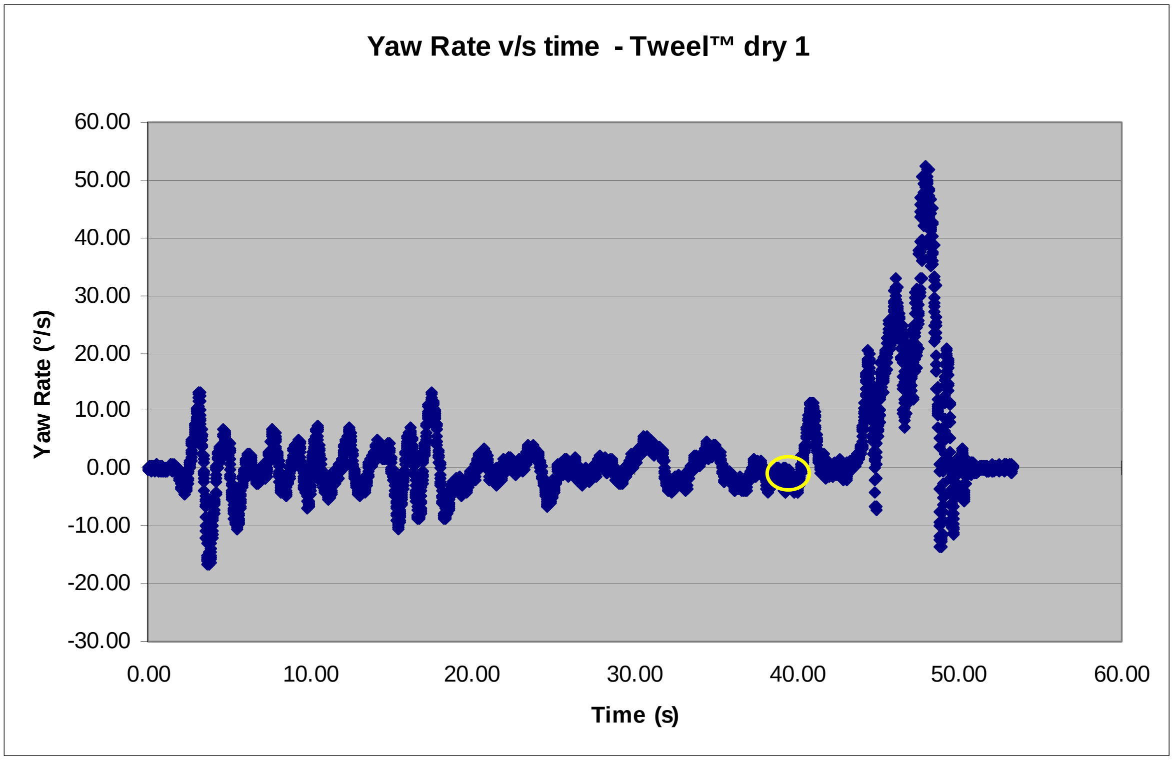



**Figure 33:Tweel™ technology tires yaw rate v/s time dry condition test 1**

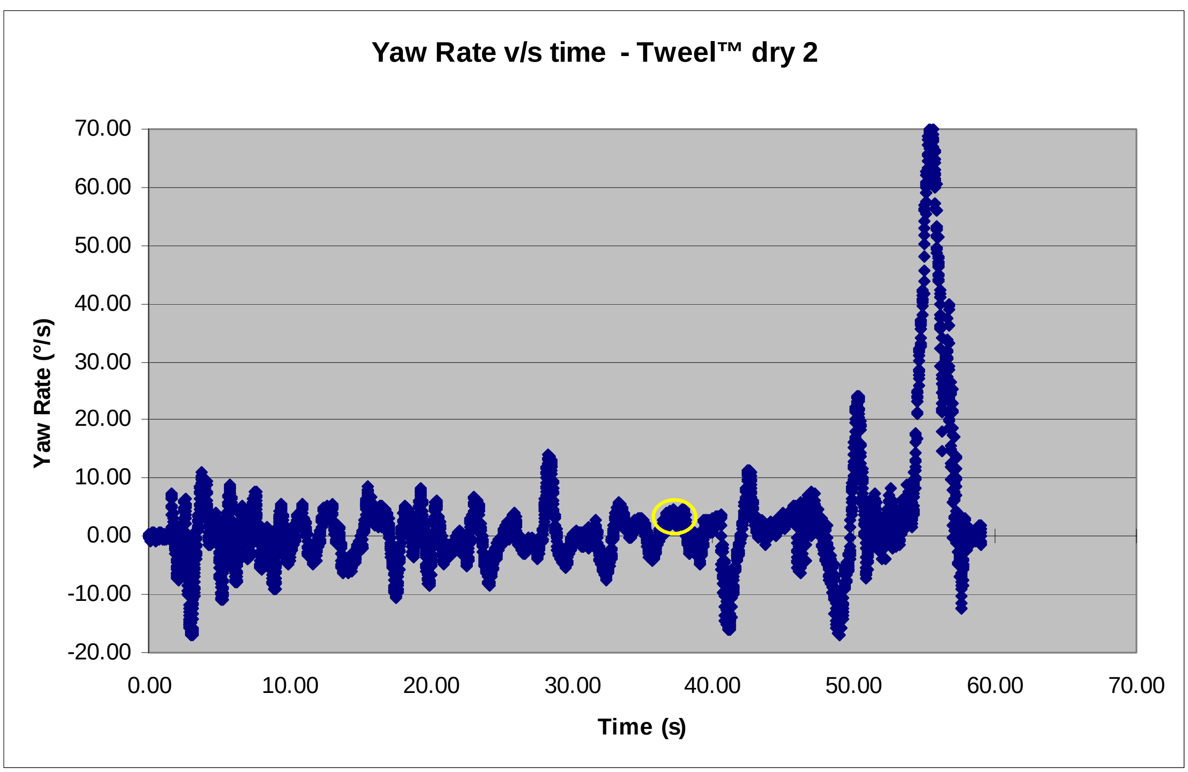



**Figure 34: Tweel™ technology tires yaw rate v/s time dry condition test 2**

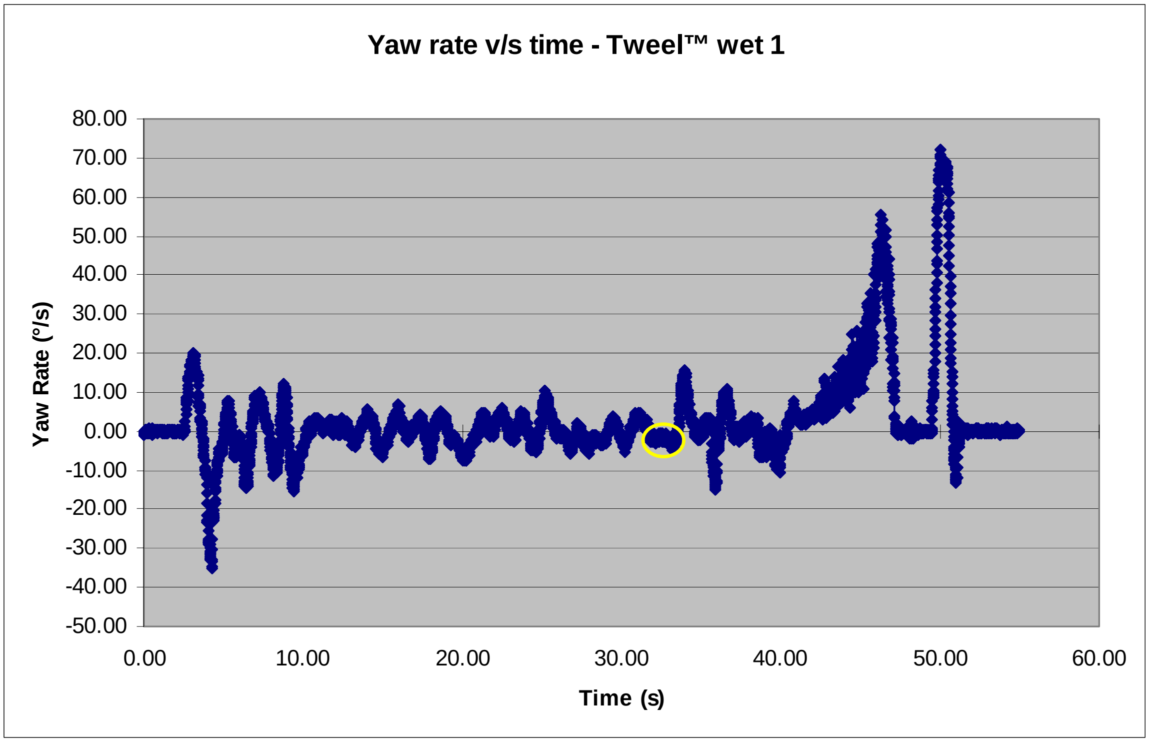



**Figure 35: Tweel™ technology tires yaw rate v/s time wet condition test 1**

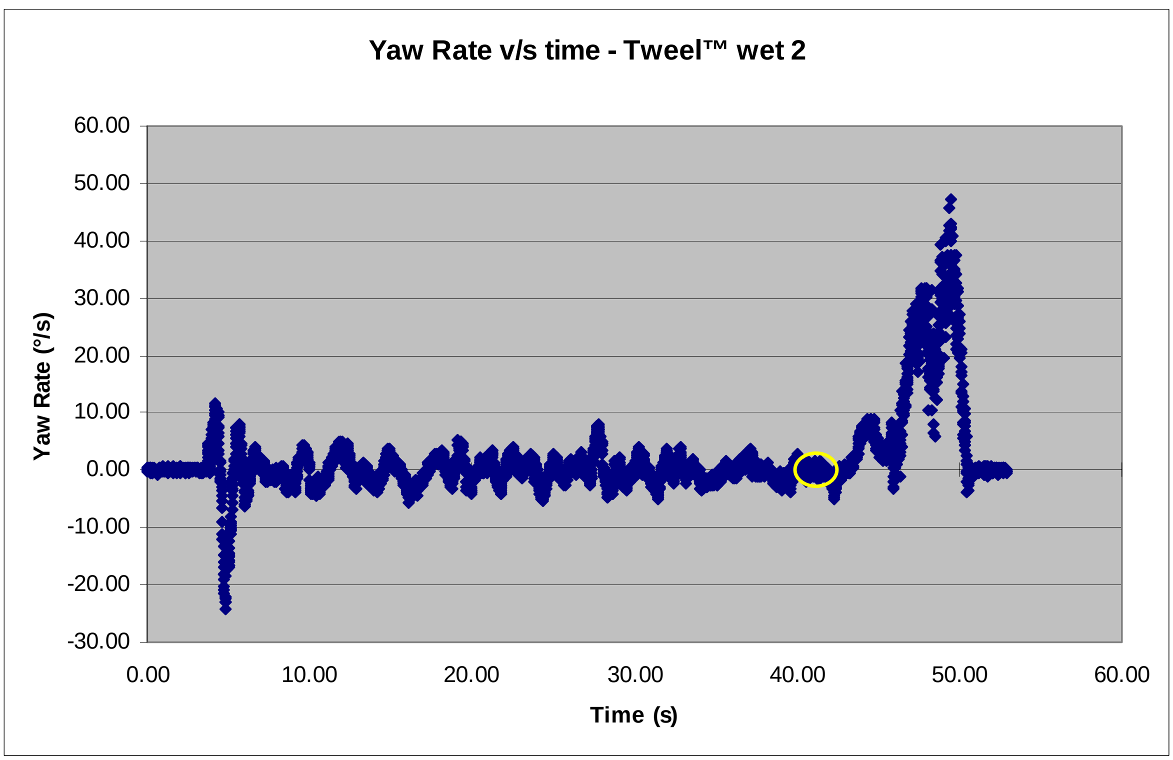



**Figure 36: Tweel™ technology tires yaw rate v/s time wet condition test 2**

# APPENDIX G

# FORCE DEFLECTION DATA

**Table 26: Force required for 5% and 10% deflection and distance for Casters**

| Subject # | Caster # | Distance Traveled | Pre 5% Force (N) | Post 5% Force (N) | Pre 10% Force (N) | Post 10% Force (N) | Loc. |
|---|---|---|---|---|---|---|---|
| 2 | 24 | 122 | 398.257 | 193.996 | 624.406 | 352.008 | 1 |
| 2 | 24 | 122 | 402.96 | 182.801 | 631.709 | 322.7 | 2 |
| 2 | 25 | 122 | 480.798 | 285.715 | 747.614 | 489.558 | 1 |
| 2 | 25 | 122 | 498.621 | 299.471 | 765.288 | 519.037 | 2 |
| 3 | 26 | 41 | 334.515 | 329.017 | 524.086 | 506.875 | 1 |
| 3 | 26 | 41 | 335.317 | 327.878 | 528.541 | 509.136 | 2 |
| 3 | 27 | 41 | 338.975 | 329.303 | 527.258 | 506.223 | 1 |
| 3 | 27 | 41 | 345.384 | 334.539 | 535.521 | 515.344 | 2 |
| 9 | 5 | 34 | 370.582 | 339.728 | 574.029 | 528.017 | 1 |
| 9 | 5 | 34 | 352.082 | 324.816 | 552.237 | 509.603 | 2 |
| 9 | 7 | 34 | 372.283 | 311.837 | 579.088 | 492.036 | 1 |
| 9 | 7 | 34 | 372.086 | 312.069 | 584.407 | 495.025 | 2 |
| 9 | 8 | 34 | 375.373 | 320.778 | 582.791 | 504.247 | 1 |
| 9 | 8 | 34 | 366.068 | 312.701 | 568.137 | 493.183 | 2 |
| 9 | 9 | 34 | 346.591 | 331.811 | 543.527 | 507.709 | 1 |
| 9 | 9 | 34 | 348.48 | 327.724 | 543.167 | 508.817 | 2 |
| 11 | 6 | 31.61 | 423.329 | 397.738 | 652.157 | 615.449 | 1 |
| 11 | 6 | 31.61 | 415.417 | 392.998 | 648.397 | 614.209 | 2 |
| 11 | 10 | 31.61 | 417.616 | 398.79 | 641.304 | 610.783 | 1 |
| 11 | 10 | 31.61 | 424.431 | 404.744 | 652.665 | 625.759 | 2 |
| 11 | 11 | 31.61 | 433.642 | 403.106 | 681.785 | 631.505 | 1 |
| 11 | 11 | 31.61 | 410.246 | 387.612 | 640.204 | 601.255 | 2 |
| 11 | 12 | 31.61 | 357.116 | 333.193 | 557.578 | 518.491 | 1 |
| 11 | 12 | 31.61 | 356.546 | 335.825 | 557.789 | 522.499 | 2 |
| 12 | 2 | 304 | 368.452 | 325.264 | 573.548 | 505.669 | 1 |
| 12 | 2 | 304 | 360.777 | 319.142 | 564.572 | 497.974 | 2 |
| 12 | 3 | 304 | 356.715 | 309.828 | 557.791 | 481.563 | 1 |
| 12 | 3 | 304 | 345.707 | 299.633 | 538.581 | 463.3 | 2 |
| 12 | 4 | 304 | 353.335 | 307.535 | 549.725 | 473.134 | 1 |
| 12 | 4 | 304 | 351.45 | 308.851 | 550.398 | 477.329 | 2 |
| 13 | 21 | 32 | 337.216 | 332.559 | 527.937 | 514.342 | 1 |
| 13 | 21 | 32 | 337.904 | 335.614 | 533.771 | 523.524 | 2 |
| 13 | 22 | 32 | 372.875 | 364.655 | 571.351 | 556.357 | 1 |
| 13 | 22 | 32 | 361.965 | 352.773 | 558.88 | 542.385 | 2 |
| 15 | 14 | 36 | 418.7 | 376.776 | 652.082 | 587.494 | 1 |

**Table 26(Continued)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15 | 14 | 36 | 408.272 | 369.828 | 633.697 | 571.183 | 2 |
| 15 | 15 | 36 | 422.018 | 391.446 | 656.574 | 610.557 | 1 |
| 15 | 15 | 36 | 417.351 | 388.515 | 646.005 | 597.421 | 2 |
| 15 | 16 | 36 | 420.743 | 361.181 | 655.7 | 572.859 | 1 |
| 15 | 16 | 36 | 417.271 | 366.327 | 654.828 | 581.919 | 2 |
| 15 | 17 | 36 | 389.313 | 363.296 | 599.755 | 557.708 | 1 |
| 15 | 17 | 36 | 378.886 | 363.451 | 585.523 | 550.869 | 2 |
| **Mean** | | **81.35** | **383.23** | **337.02** | **596.53** | **527.74** | |

**Table 27: Reduction in force required for 5% and 10% deflection and distance traveled for Casters**

| Subject # | Caster# | Distance Traveled | Reduction in 5% Force (N) | %Δ in 5% force | Reduction in 10% Force (N) | %Δ in 10% force | Loc. |
|---|---|---|---|---|---|---|---|
| 2 | 24 | 122 | 204.261 | 51.3 | 272.398 | 43.6 | 1 |
| 2 | 24 | 122 | 220.159 | 54.6 | 309.009 | 48.9 | 2 |
| 2 | 25 | 122 | 195.083 | 40.6 | 258.056 | 34.5 | 1 |
| 2 | 25 | 122 | 199.15 | 39.9 | 246.251 | 32.2 | 2 |
| 3 | 26 | 41 | 5.498 | 1.6 | 17.211 | 3.3 | 1 |
| 3 | 26 | 41 | 7.439 | 2.2 | 19.405 | 3.7 | 2 |
| 3 | 27 | 41 | 9.672 | 2.9 | 21.035 | 4.0 | 1 |
| 3 | 27 | 41 | 10.845 | 3.1 | 20.177 | 3.8 | 2 |
| 9 | 5 | 34 | 30.854 | 8.3 | 46.012 | 8.0 | 1 |
| 9 | 5 | 34 | 27.266 | 7.7 | 42.634 | 7.7 | 2 |
| 9 | 7 | 34 | 60.446 | 16.2 | 87.052 | 15.0 | 1 |
| 9 | 7 | 34 | 60.017 | 16.1 | 89.382 | 15.3 | 2 |
| 9 | 8 | 34 | 54.595 | 14.5 | 78.544 | 13.5 | 1 |
| 9 | 8 | 34 | 53.367 | 14.6 | 74.954 | 13.2 | 2 |
| 9 | 9 | 34 | 14.78 | 4.3 | 35.818 | 6.6 | 1 |
| 9 | 9 | 34 | 20.756 | 6.0 | 34.35 | 6.3 | 2 |
| 11 | 6 | 31.61 | 25.591 | 6.0 | 36.708 | 5.6 | 1 |
| 11 | 6 | 31.61 | 22.419 | 5.4 | 34.188 | 5.3 | 2 |
| 11 | 10 | 31.61 | 18.826 | 4.5 | 30.521 | 4.8 | 1 |
| 11 | 10 | 31.61 | 19.687 | 4.6 | 26.906 | 4.1 | 2 |
| 11 | 11 | 31.61 | 30.536 | 7.0 | 50.28 | 7.4 | 1 |
| 11 | 11 | 31.61 | 22.634 | 5.5 | 38.949 | 6.1 | 2 |
| 11 | 12 | 31.61 | 23.923 | 6.7 | 39.087 | 7.0 | 1 |
| 11 | 12 | 31.61 | 20.721 | 5.8 | 35.29 | 6.3 | 2 |
| 12 | 2 | 304 | 43.188 | 11.7 | 67.879 | 11.8 | 1 |

**Table 27 (Continued)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | 2 | 304 | 41.635 | 11.5 | 66.598 | 11.8 | 2 |
| 12 | 3 | 304 | 46.887 | 13.1 | 76.228 | 13.7 | 1 |
| 12 | 3 | 304 | 46.074 | 13.3 | 75.281 | 14.0 | 2 |
| 12 | 4 | 304 | 45.8 | 13.0 | 76.591 | 13.9 | 1 |
| 12 | 4 | 304 | 42.599 | 12.1 | 73.069 | 13.3 | 2 |
| 13 | 21 | 32 | 4.657 | 1.4 | 13.595 | 2.6 | 1 |
| 13 | 21 | 32 | 2.29 | 0.7 | 10.247 | 1.9 | 2 |
| 13 | 22 | 32 | 8.22 | 2.2 | 14.994 | 2.6 | 1 |
| 13 | 22 | 32 | 9.192 | 2.5 | 16.495 | 3.0 | 2 |
| 15 | 14 | 36 | 41.924 | 10.0 | 64.588 | 9.9 | 1 |
| 15 | 14 | 36 | 38.444 | 9.4 | 62.514 | 9.9 | 2 |
| 15 | 15 | 36 | 30.572 | 7.2 | 46.017 | 7.0 | 1 |
| 15 | 15 | 36 | 28.836 | 6.9 | 48.584 | 7.5 | 2 |
| 15 | 16 | 36 | 59.562 | 14.2 | 82.841 | 12.6 | 1 |
| 15 | 16 | 36 | 50.944 | 12.2 | 72.909 | 11.1 | 2 |
| 15 | 17 | 36 | 26.017 | 6.7 | 42.047 | 7.0 | 1 |
| 15 | 17 | 36 | 15.435 | 4.1 | 34.654 | 5.9 | 2 |
| **Mean** | | **81.35** | **46.21** | **11.48** | **68.79** | **11.09** | |

**Table 28: Force required for 5% and 10% deflection and distance traveled for Drive Wheels**

| Subject # | Drive Wheel# | Distance Traveled | Pre 5% Force (N) | Post 5% Force (N) | Pre 10% Force (N) | Post 10% Force (N) | Loc. |
|---|---|---|---|---|---|---|---|
| 4 | 6 | 94.5 | 719.251 | 634.717 | 1141.63 | 1022.08 | 1 |
| 4 | 6 | 94.5 | 707.923 | 614.371 | 1117.36 | 996.825 | 2 |
| 4 | 7 | 94.5 | 712.636 | 619.651 | 1113.25 | 992.114 | 1 |
| 4 | 7 | 94.5 | 695.546 | 597.734 | 1098.93 | 957.015 | 2 |
| 5 | 14 | 25.45 | 679.859 | 614.931 | 1070.35 | 972.264 | 1 |
| 5 | 14 | 25.45 | 680.13 | 610.143 | 1082.38 | 978.882 | 2 |
| 5 | 15 | 25.45 | 777.771 | 686.843 | 1223.95 | 1115.71 | 1 |
| 5 | 15 | 25.45 | 755.418 | 666.591 | 1186.9 | 1080.68 | 2 |
| 8 | 8 | 66 | 702.759 | 633.132 | 1109.24 | 1011.48 | 1 |
| 8 | 8 | 66 | 693.848 | 628.711 | 1089.91 | 1005.11 | 2 |
| 8 | 9 | 66 | 720.02 | 637.288 | 1144.26 | 1008.2 | 1 |
| 8 | 9 | 66 | 716.836 | 628.82 | 1135.68 | 1003.34 | 2 |
| 12 | 4 | 219 | 687.515 | 591.869 | 1103.52 | 953.738 | 1 |
| 12 | 4 | 219 | 709.344 | 593.72 | 1131.94 | 957.355 | 2 |
| 12 | 5 | 219 | 692.191 | 583.031 | 1108.32 | 950.29 | 1 |
| 12 | 5 | 219 | 678.382 | 577.212 | 1069.6 | 937.625 | 2 |
| 15 | 11 | 36 | 677.845 | 614.399 | 1070.91 | 988.725 | 1 |

**Table 28 (Continued)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15 | 11 | 36 | 702.007 | 630.946 | 1101.74 | 1008.55 | 2 |
| 15 | 12 | 36 | 737.434 | 642.078 | 1165.69 | 1043.6 | 1 |
| 15 | 12 | 36 | 746.859 | 654.361 | 1176.85 | 1037.52 | 2 |
| **Mean** | | **88.2** | **709.68** | **623.03** | **1122.12** | **1001.06** | |

**Table 29: Reduction in force required for 5% and 10% deflection and distance traveled Drive wheels**

| Subject # | Drive Wheel# | Distance Traveled | Reduction in 5% Force (N) | %Δ in 5% force | Reduction in 10% Force (N) | %Δ in 10% force | Loc. |
|---|---|---|---|---|---|---|---|
| 4 | 6 | 94.5 | 84.534 | 11.8 | 119.55 | 10.5 | 1 |
| 4 | 6 | 94.5 | 93.552 | 13.2 | 120.535 | 10.8 | 2 |
| 4 | 7 | 94.5 | 92.985 | 13.0 | 121.136 | 10.9 | 1 |
| 4 | 7 | 94.5 | 97.812 | 14.1 | 141.915 | 12.9 | 2 |
| 5 | 14 | 25.45 | 64.928 | 9.6 | 98.086 | 9.2 | 1 |
| 5 | 14 | 25.45 | 69.987 | 10.3 | 103.498 | 9.6 | 2 |
| 5 | 15 | 25.45 | 90.928 | 11.7 | 108.24 | 8.8 | 1 |
| 5 | 15 | 25.45 | 88.827 | 11.8 | 106.22 | 8.9 | 2 |
| 8 | 8 | 66 | 69.627 | 9.9 | 97.76 | 8.8 | 1 |
| 8 | 8 | 66 | 65.137 | 9.4 | 84.8 | 7.8 | 2 |
| 8 | 9 | 66 | 82.732 | 11.5 | 136.06 | 11.9 | 1 |
| 8 | 9 | 66 | 88.016 | 12.3 | 132.34 | 11.7 | 2 |
| 12 | 4 | 219 | 95.646 | 13.9 | 149.782 | 13.6 | 1 |
| 12 | 4 | 219 | 115.624 | 16.3 | 174.585 | 15.4 | 2 |
| 12 | 5 | 219 | 109.16 | 15.8 | 158.03 | 14.3 | 1 |
| 12 | 5 | 219 | 101.17 | 14.9 | 131.975 | 12.3 | 2 |
| 15 | 11 | 36 | 63.446 | 9.4 | 82.185 | 7.7 | 1 |
| 15 | 11 | 36 | 71.061 | 10.1 | 93.19 | 8.5 | 2 |
| 15 | 12 | 36 | 95.356 | 12.9 | 122.09 | 10.5 | 1 |
| 15 | 12 | 36 | 92.498 | 12.4 | 139.33 | 11.8 | 2 |
| **Mean** | | **88.2** | **86.65** | **12.21** | **121.07** | **10.79** | |

# APPENDIX H

# VISUAL INSPECTION OF WEAR AND DAMAGE

The following documentation has been broken down by subject and the specific Tweel™ technology tires they had installed on their power wheelchairs. The information for each field trial subject includes: Tweel™ type, Wheelchair type, self-reported weight of participant, odometer reading, photographs of and any damage to the Tweel™ tires, a written description of the condition of wheels, pre/post force deflection results. All Tweel™ tires were used for approximately 4-5 weeks.

**<u>Subject 2</u>**

Tweel™ Used: 2 Tweel™ casters, front wheels.

Wheelchair Type: Invacare Action Ranger

Approximate weight of user: 225 lbs.

Odometer Reading: 122 miles.

Usage Dates: 3/31/2006 – 5/16/2006 (46 days)

**Table 30: Subject 2 Tweel™ technology tire properties**

| C # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 24 | 398.257 | 193.996 | 624.406 | 352.008 | 204.261 | 272.398 |
| 24 | 402.96 | 182.801 | 631.709 | 322.7 | 220.159 | 309.009 |
| 25 | 480.798 | 285.715 | 747.614 | 489.558 | 195.083 | 258.056 |
| 25 | 498.621 | 299.471 | 765.288 | 519.037 | 199.15 | 246.251 |

There was significant deformation of the caster spokes. There was no visible damage but there was excessive wear to the casters.


**Figure 37: Subject 2 Tweel™ casters after field trial - 1**


**Figure 38: Subject 2 Tweel™ casters after field trial - 2**


**Figure 39: Subject 2 Tweel™ casters after field trial - 3**

**<u>Subject 3</u>**

Tweel™ Used:  2 Tweel™ caters, front wheels

Wheelchair Type:  Quickie V-121

Approximate weight of user:  200 lbs.

Odometer Reading:  41 miles.

Usage Dates: 4/07/2006 – 5/09/2006 (32 days)

**Table 31: Subject 3 Tweel™ technology tire properties**

| C # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 26 | 334.515 | 329.017 | 524.086 | 506.875 | 5.498 | 17.211 |
| 26 | 335.317 | 327.878 | 528.541 | 509.136 | 7.439 | 19.405 |
| 27 | 338.975 | 329.303 | 527.258 | 506.223 | 9.672 | 21.035 |
| 27 | 345.384 | 334.539 | 535.521 | 515.344 | 10.845 | 20.177 |

The casters had wear but the most noticeable issue was a small pit in the center of one of the caster wheels.


**Figure 40: Subject 3 Tweel™ casters after field trial - 1**


**Figure 41: Subject 3 Tweel™ casters after field trial - 2**

**Subject 4**

Tweel™ Used: 2 Tweel™ drive wheels.

Wheelchair Type: Quickie P-222

Approximate weight of user: 240 lbs.

Odometer Reading: 94.5 miles.

Usage Dates: 3/29/2006 – 5/05/2006 (37 days)

**Table 32: Subject 4 Tweel™ technology tire properties**

| D # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 6 | 719.251 | 634.717 | 1141.63 | 1022.08 | 84.534 | 119.55 |
| 6 | 707.923 | 614.371 | 1117.36 | 996.825 | 93.552 | 120.535 |
| 7 | 712.636 | 619.651 | 1113.25 | 992.114 | 92.985 | 121.136 |
| 7 | 695.546 | 597.734 | 1098.93 | 957.015 | 97.812 | 141.915 |

There was minimal damage to the Tweel™ drive wheel. Only a few areas where the tread, on both drive Tweels, where some damage occurred.


**Figure 42: Subject 4 Tweel$^{TM}$ drive wheels after field trial - 1**

**Figure 43: Subject 4 Tweel$^{TM}$ drive wheels after field trial - 2**

**<u>Subject 5</u>**

Tweel™ Used: 2 Tweel™ drive wheels.

Wheelchair Type: Invacare Torque

Approximate weight of user: 150 lbs.

Odometer Reading: 25.5 miles.

Usage Dates: 4/05/2006 – 5/05/2006 (30 days)

**Table 33: Subject 5 Tweel™ technology tire properties**

| D # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 14 | 679.859 | 614.931 | 1070.35 | 972.264 | 64.928 | 98.086 |
| 14 | 680.13 | 610.143 | 1082.38 | 978.882 | 69.987 | 103.498 |
| 15 | 777.771 | 686.843 | 1223.95 | 1115.71 | 90.928 | 108.24 |
| 15 | 755.418 | 666.591 | 1186.9 | 1080.68 | 88.827 | 106.22 |

There was significant damage to outside edge of the right side Tweel™ drive wheel Most of the outside edge has been torn off, probably because of a metal ramp. There were a few pits removed from the tread. There was some outside edge damage to the Tweel™ tire on the left side of the wheelchair.


**Figure 44: Subject 5 Tweel™ drive wheels after field trial - 1**

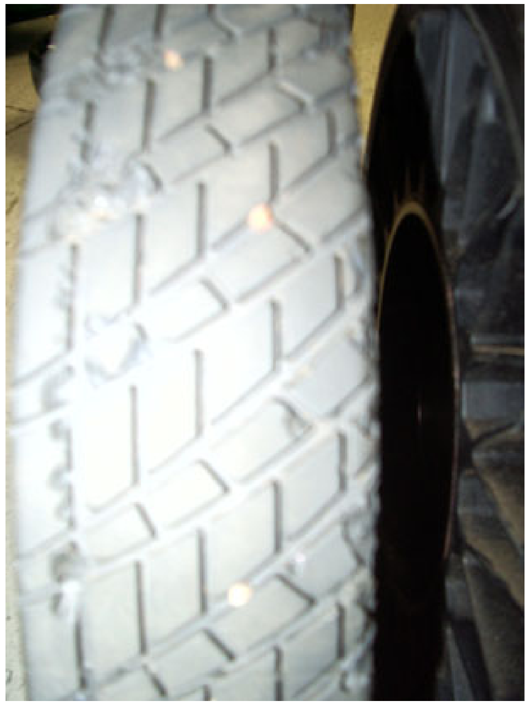


**Figure 45: Subject 5 Tweel™ drive wheels after field trial - 2**

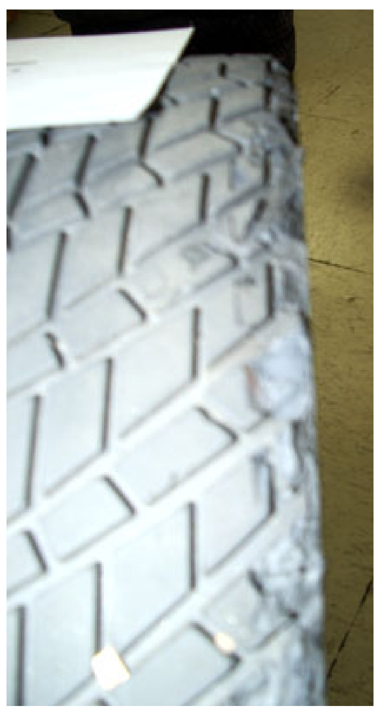


**Figure 46: Subject 5 Tweel™ drive wheels after field trial - 3**

**Subject 8**

Tweel™ Used: 2 Tweel™ drive wheels.

Wheelchair Type: Jazzy 1122

Approximate weight of user: 145 lbs.

Odometer Reading: 66 miles.

Usage Dates: 3/28/2006 – 5/01/2006 (34 days)

**Table 34: Subject 8 Tweel™ technology tire properties**

| D # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 8 | 702.759 | 633.132 | 1109.24 | 1011.48 | 69.627 | 97.76 |
| 8 | 693.848 | 628.711 | 1089.91 | 1005.11 | 65.137 | 84.8 |
| 9 | 720.02 | 637.288 | 1144.26 | 1008.2 | 82.732 | 136.06 |
| 9 | 716.836 | 628.82 | 1135.68 | 1003.34 | 88.016 | 132.34 |

There was only minor edge damage to the Tweel™ drive wheel.


**Figure 47: Subject 8 Tweel™ drive wheels after field trial**

**Subject 9**

Tweel™ Used: 4 Tweel™ casters.

Wheelchair Type: Invacare Storm TDX 5.

Approximate weight of user: 250 lbs.

Odometer Reading: 34 miles.

Usage Dates: 3/03/2006 – 4/14/2006 (41 days)

**Table 35: Subject 9 Tweel™ technology tire properties**

| C # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 5 | 370.582 | 339.728 | 574.029 | 528.017 | 30.854 | 46.012 |
| 5 | 352.082 | 324.816 | 552.237 | 509.603 | 27.266 | 42.634 |
| 7 | 372.283 | 311.837 | 579.088 | 492.036 | 60.446 | 87.052 |
| 7 | 372.086 | 312.069 | 584.407 | 495.025 | 60.017 | 89.382 |
| 8 | 375.373 | 320.778 | 582.791 | 504.247 | 54.595 | 78.544 |
| 8 | 366.068 | 312.701 | 568.137 | 493.183 | 53.367 | 74.954 |
| 9 | 346.591 | 331.811 | 543.527 | 507.709 | 14.78 | 35.818 |
| 9 | 348.48 | 327.724 | 543.167 | 508.817 | 20.756 | 34.35 |

There was damage to only one of the Tweel™ casters. The removal of the urethane tread was over the entire tread area. There was no damage to any of the other casters.


**Figure 48: Subject 9 Tweel™ casters after field trial -1**

**Figure 49: Subject 9 Tweel™ caster after field trial -2**

**Subject 11**

Tweel™ Used: 4 Tweel™ casters.

Wheelchair Type: Invacare TDX 3

Approximate weight of user: 175 lbs.

Odometer Reading: 31.5 miles.

Usage Dates: 3/06/2006 -4/21/2006 (46 days)

**Table 36: Subject 11 Tweel™ technology tire properties**

| C # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 6 | 423.329 | 397.738 | 652.157 | 615.449 | 25.591 | 36.708 |
| 6 | 415.417 | 392.998 | 648.397 | 614.209 | 22.419 | 34.188 |
| 10 | 417.616 | 398.79 | 641.304 | 610.783 | 18.826 | 30.521 |
| 10 | 424.431 | 404.744 | 652.665 | 625.759 | 19.687 | 26.906 |
| 11 | 433.642 | 403.106 | 681.785 | 631.505 | 30.536 | 50.28 |
| 11 | 410.246 | 387.612 | 640.204 | 601.255 | 22.634 | 38.949 |
| 12 | 357.116 | 333.193 | 557.578 | 518.491 | 23.923 | 39.087 |
| 12 | 356.546 | 335.825 | 557.789 | 522.499 | 20.721 | 35.29 |

There was no visible damage to the Tweel™ casters. There was wear but the parting line was still visible.


**Figure 50: Subject 11 Tweel™ casters after field trial**

**Subject 12**

Tweel™ Used: 4 Tweel™ casters, 2 Tweel™ drive wheels.

Wheelchair Type: Invacare TDX 4

Approximate weight of user: 125 lbs.

Odometer Reading: 304 miles (casters) 219 miles (drive wheels).

Usage Dates: 3/01/2006 – 5/20/2006 (80days) (Casters)

3/24/2006 – 5/20/2006 (57 days) (Drive Wheels)

**Table 37: Subject 12 Tweel™ caster properties**

| C. # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 1* | 358.03 | 264.973 | 560.598 | 443.118 | 93.057 | 117.48 |
| 1* | 354.102 | 242.068 | 553.22 | 390.659 | 112.034 | 162.561 |
| 2 | 368.452 | 325.264 | 573.548 | 505.669 | 43.188 | 67.879 |
| 2 | 360.777 | 319.142 | 564.572 | 497.974 | 41.635 | 66.598 |
| 3 | 356.715 | 309.828 | 557.791 | 481.563 | 46.887 | 76.228 |
| 3 | 345.707 | 299.633 | 538.581 | 463.3 | 46.074 | 75.281 |
| 3** | | 303.621 | | 475.837 | | |
| 4 | 353.335 | 307.535 | 549.725 | 473.134 | 45.8 | 76.591 |
| 4 | 351.45 | 308.851 | 550.398 | 477.329 | 42.599 | 73.069 |

*The values were not used for other calculations as the casters were removed before the end of the experiment

**At the location of the torn fin

**Table 38: Subject 12 Tweel™ drive wheel properties**

| D # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 4 | 687.515 | 591.869 | 1103.52 | 953.738 | 95.646 | 149.782 |
| 4 | 709.344 | 593.72 | 1131.94 | 957.355 | 115.624 | 174.585 |
| 5 | 692.191 | 583.031 | 1108.32 | 950.29 | 109.16 | 158.03 |
| 5 | 678.382 | 577.212 | 1069.6 | 937.625 | 101.17 | 131.975 |

There was some visible damage to the tread of the drive wheels, particularly on the outside edges. Tread wear was noticed on all of the Casters and 2 of them had significant damages. One of the casters (1) developed visible flat spots probably from getting stuck and being dragged along and had to be replaced. One of the urethane fins on a casters (3) was torn on the inside edge.


**Figure 51: Subject 12 Tweel$^{TM}$ drive wheels after field trial - 1**

**Figure 52: Subject 12 Tweel$^{TM}$ drive wheel after field trial - 2**


**Figure 53: Subject 12 Tweel$^{TM}$ casters after field trial - 1**

**Figure 54: Subject 12 Tweel™ casters after field trial - 2**

**Figure 55: Subject 12 Tweel™ casters # 1after field trial - 1**

**Figure 56: Subject 12 Tweel™ casters # 1 after field trial - 2**

**Figure 57: Subject 12 Tweel™ casters # 3 after field trial**

**<u>Subject 13</u>**

Tweel™ Used: 2 Tweel™ casters, rear wheels.

Wheelchair Type: Invacare X-Terra GT

Approximate weight of user: 250 lbs.

Odometer Reading: 32 miles.

Usage Dates: 3/24/2006 – 4/24/2006 (31 days)

**Table 39: Subject 13 Tweel™ technology tire properties**

| C # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 21 | 337.216 | 332.559 | 527.937 | 514.342 | 4.657 | 13.595 |
| 21 | 337.904 | 335.614 | 533.771 | 523.524 | 2.29 | 10.247 |
| 22 | 372.875 | 364.655 | 571.351 | 556.357 | 8.22 | 14.994 |
| 22 | 361.965 | 352.773 | 558.88 | 542.385 | 9.192 | 16.495 |

No damage to casters and only minimal wear to tread.


**Figure 58: Subject 13 Tweel$^{TM}$ casters after field trial**

**<u>Subject 15</u>**

Tweel™ Used: 4 Tweel™ casters, 2 Tweel™ drive wheels.

Wheelchair Type: Invacare TDX 3

Approximate weight of user: 140 lbs.

Odometer Reading: 36 miles.

Usage Dates: 3/28/2006 – 5/9/2006 (42 days)

**Table 40: Subject 15 Tweel™ technology tire properties**

| C. # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 14 | 418.7 | 376.776 | 652.082 | 587.494 | 41.924 | 64.588 |
| 14 | 408.272 | 369.828 | 633.697 | 571.183 | 38.444 | 62.514 |
| 15 | 422.018 | 391.446 | 656.574 | 610.557 | 30.572 | 46.017 |
| 15 | 417.351 | 388.515 | 646.005 | 597.421 | 28.836 | 48.584 |
| 16 | 420.743 | 361.181 | 655.7 | 572.859 | 59.562 | 82.841 |
| 16 | 417.271 | 366.327 | 654.828 | 581.919 | 50.944 | 72.909 |
| 17 | 389.313 | 363.296 | 599.755 | 557.708 | 26.017 | 42.047 |
| 17 | 378.886 | 363.451 | 585.523 | 550.869 | 15.435 | 34.654 |

| D # | Pre 5% (N) | Post 5% (N) | Pre 10% (N) | Post 10% (N) | Diff. 5% (N) | Diff. 10% (N) |
|---|---|---|---|---|---|---|
| 11 | 677.845 | 614.399 | 1070.91 | 988.725 | 63.446 | 82.185 |
| 11 | 702.007 | 630.946 | 1101.74 | 1008.55 | 71.061 | 93.19 |
| 12 | 737.434 | 642.078 | 1165.69 | 1043.6 | 95.356 | 122.09 |
| 12 | 746.859 | 654.361 | 1176.85 | 1037.52 | 92.498 | 139.33 |

There was no visible damage to the Tweel™ casters but some wear noticed. The Tweel™ drive wheels had some damage to the outside edge of the right Tweel™ drive wheel. There was a lot of debris caught in the tread.


**Figure 59: Subject 15 Tweel™ casters after field trial - 1**


**Figure 60: Subject 15 Tweel$^{TM}$ casters after field trial - 2**


**Figure 61: Subject 15 Tweel$^{TM}$ drive wheels after field trial**

# APPENDIX I

# MOVING AND STATIONARY TURN TESTING

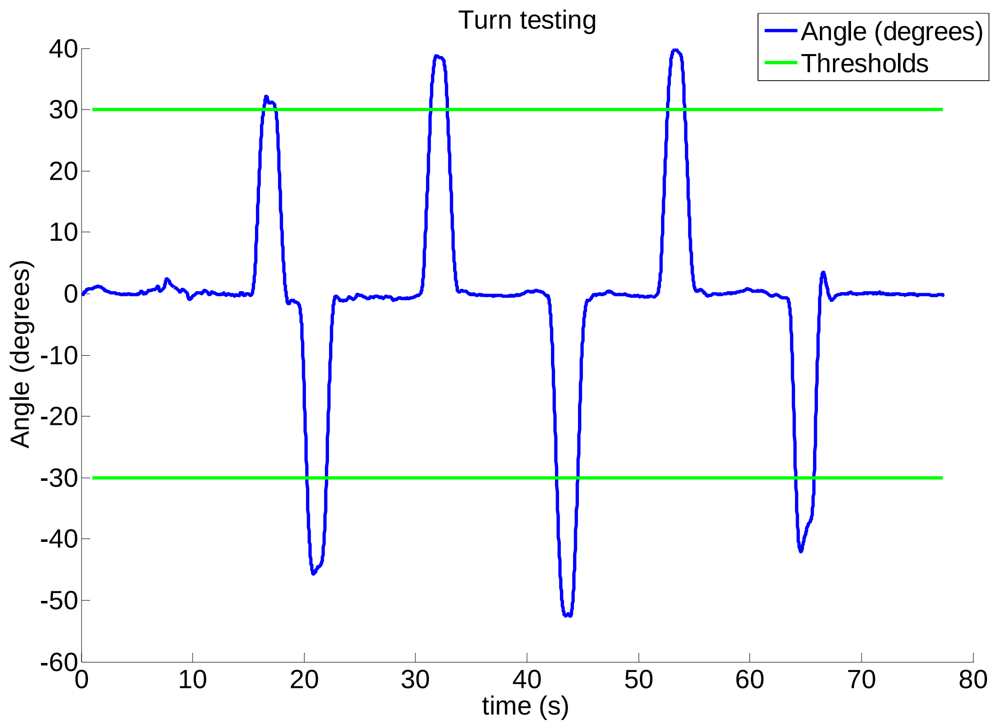



**Figure 62: Stationary turn test # 1**

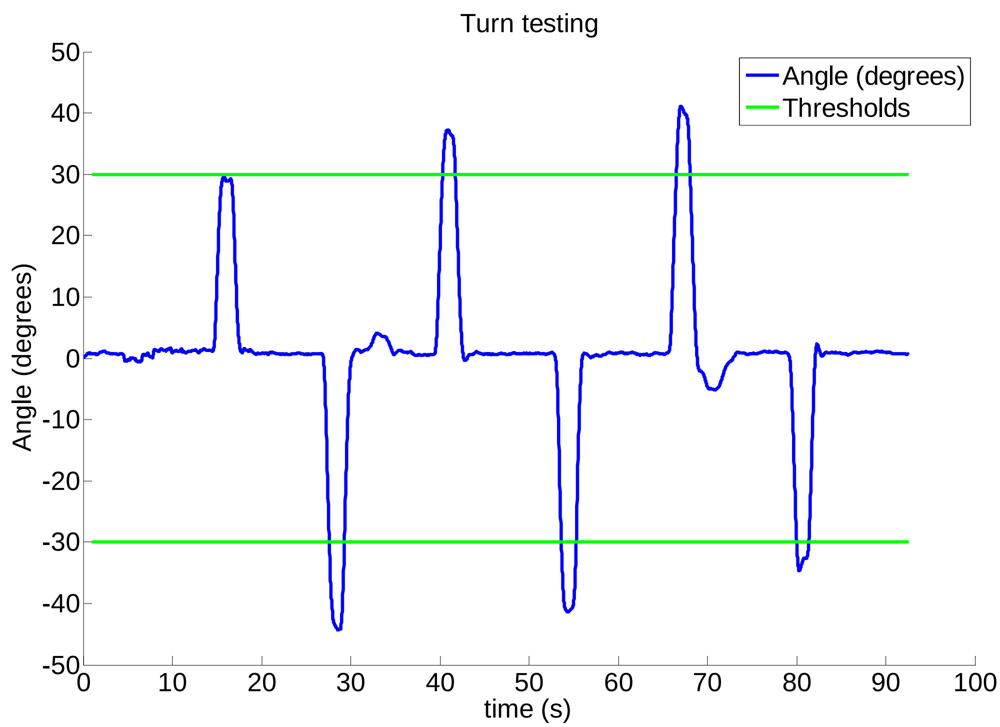



**Figure 63: Stationary turn test # 2**

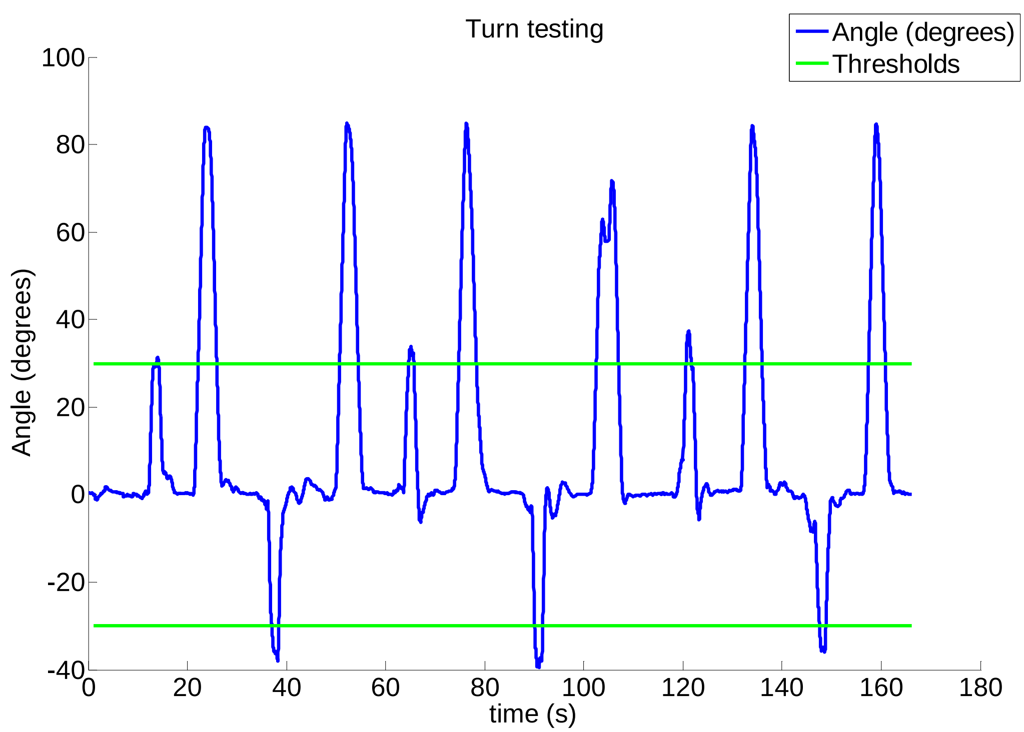



**Figure 64: Moving turn test # 1**

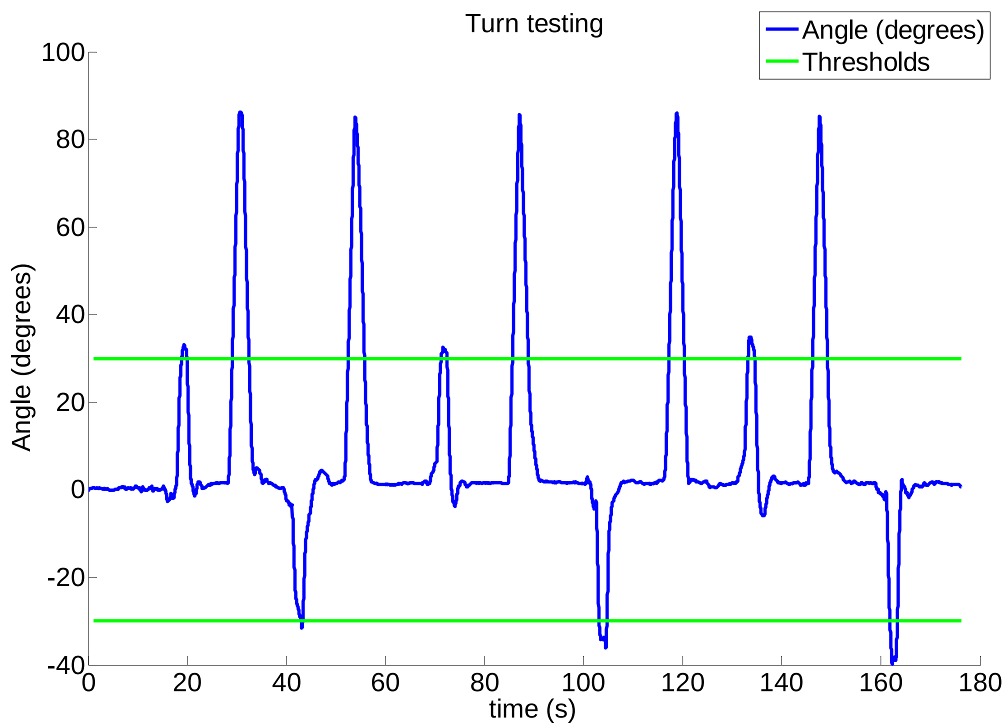



**Figure 65: Moving turn test # 2**

# APPENDIX J

# INDOOR AND OUTDOOR ACCURACY TESTING GRAPHS

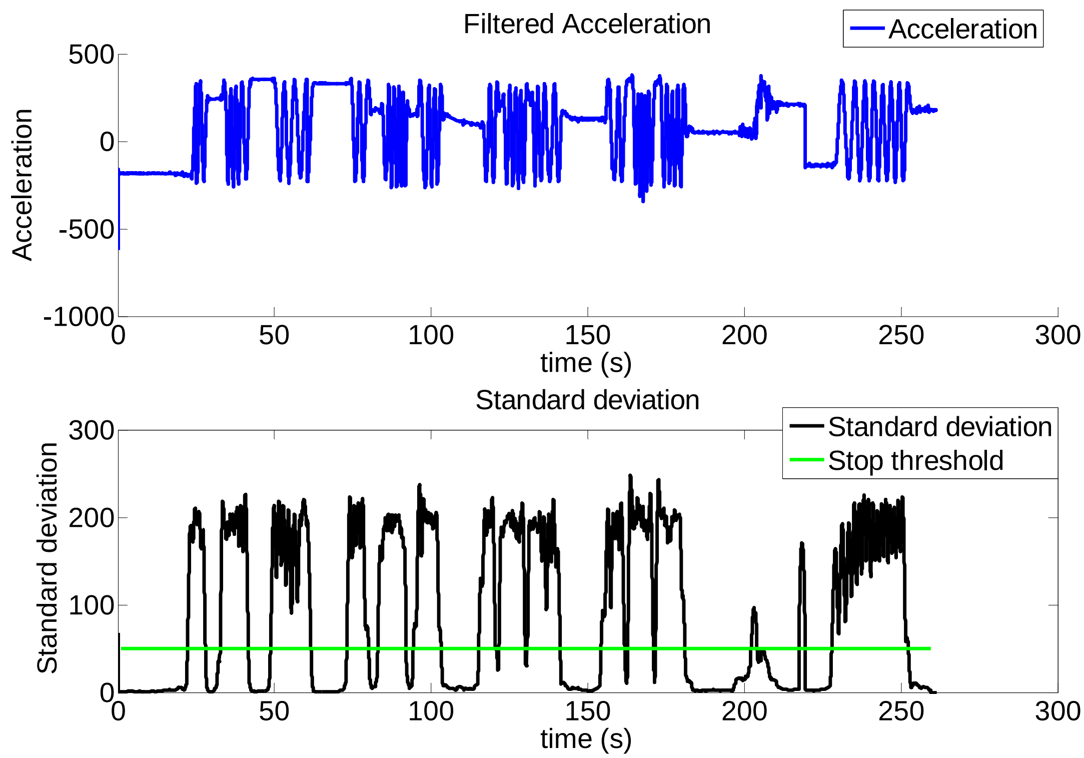



**Figure 66: Indoor testing acceleration profile and standard deviation subject 1 - right wheel**

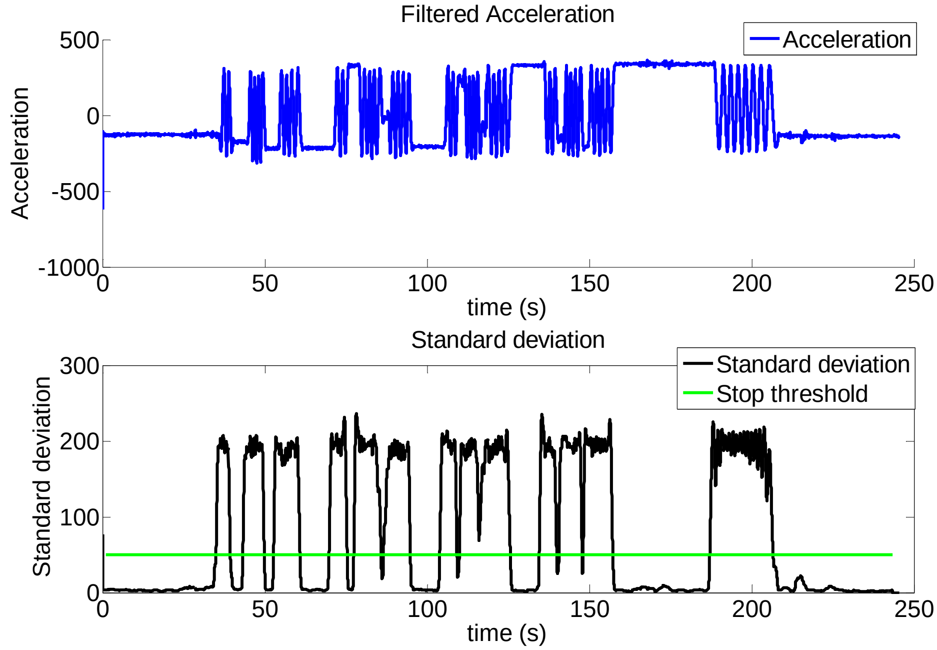



**Figure 67: Indoor testing acceleration profile and standard deviation subject 2 - right wheel**

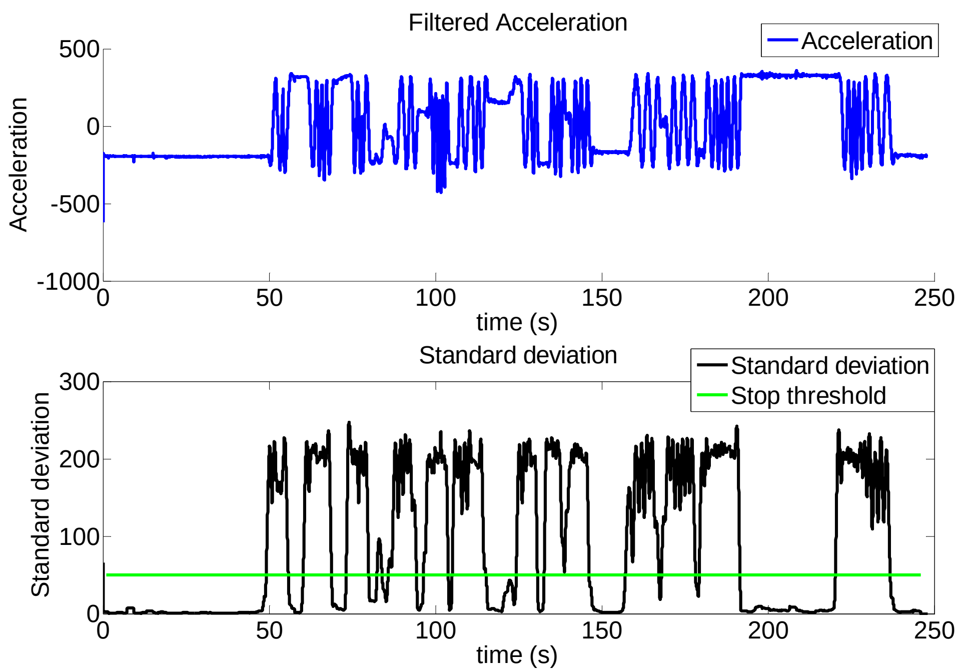



**Figure 68: Indoor testing acceleration profile and standard deviation subject 3 - right wheel**

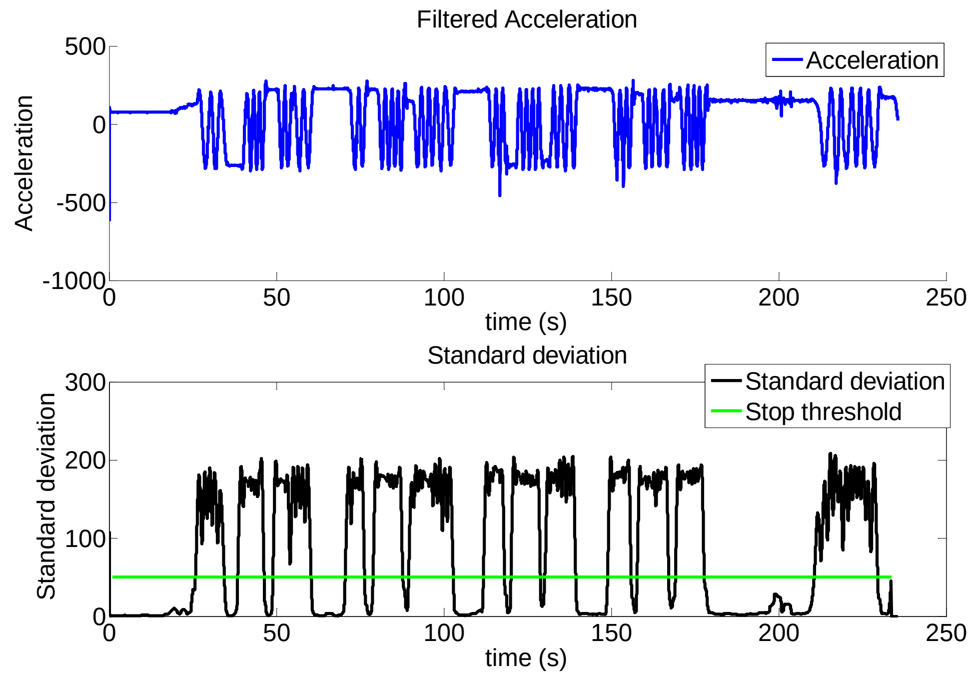



**Figure 69: Indoor testing acceleration profile and standard deviation subject 4 - right wheel**

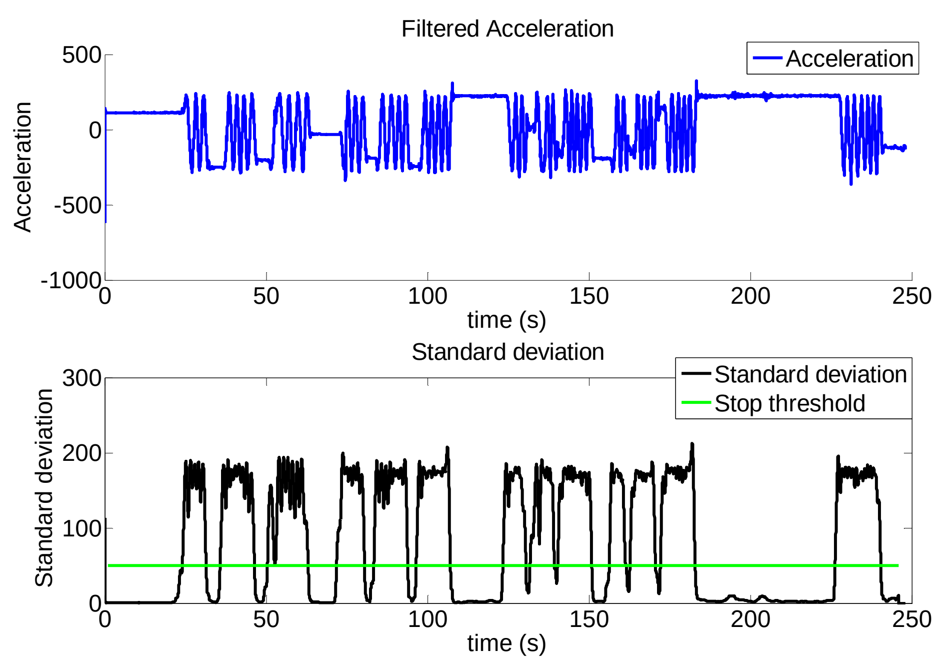



**Figure 70: Indoor testing acceleration profile and standard deviation subject 5 - right wheel**

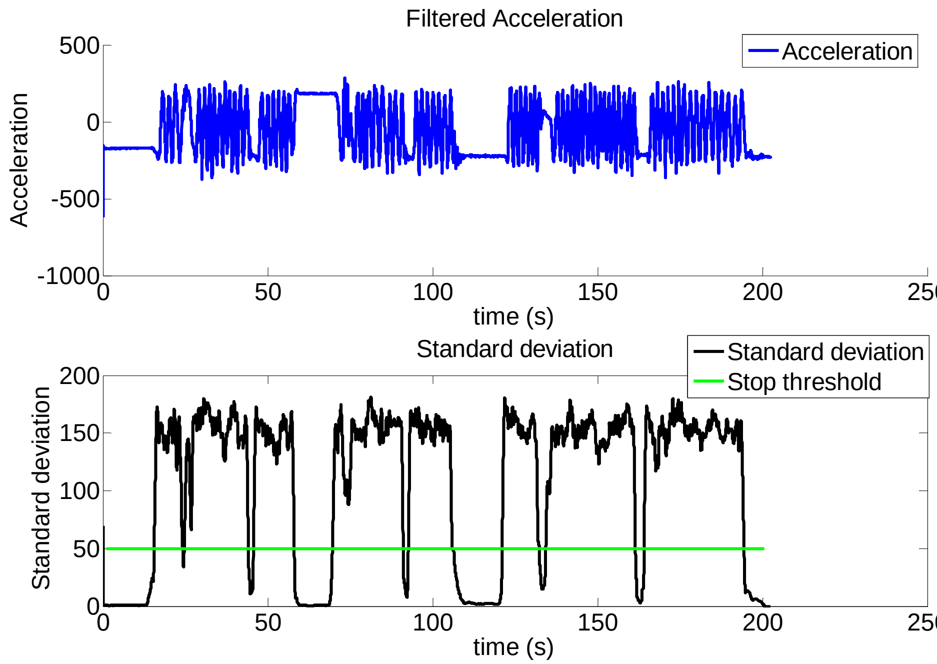



**Figure 71: Outdoor testing acceleration profile and standard deviation subject 1 - right wheel**

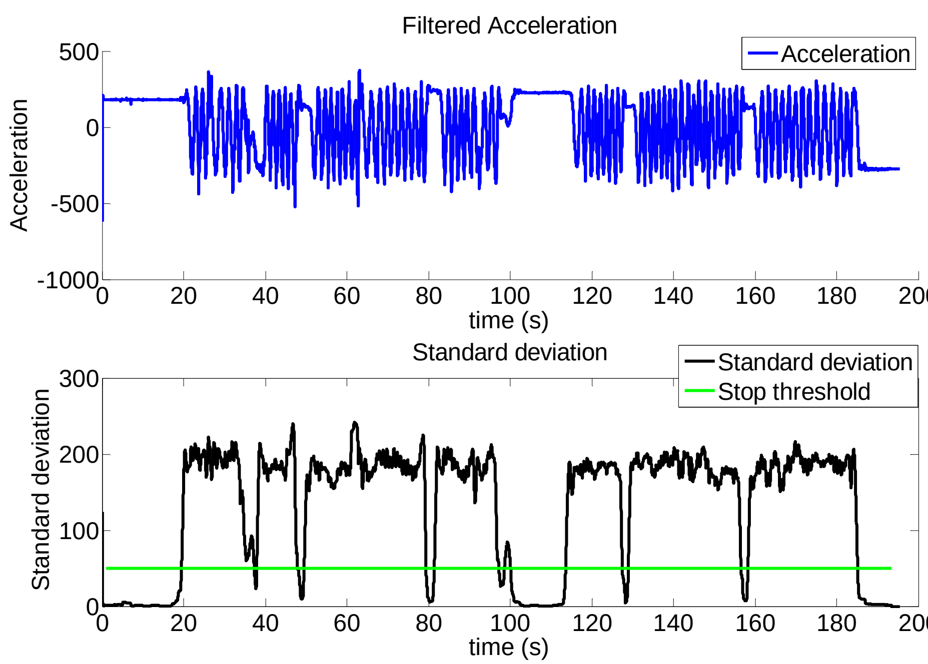



**Figure 72: Outdoor testing acceleration profile and standard deviation subject 2 - right wheel**

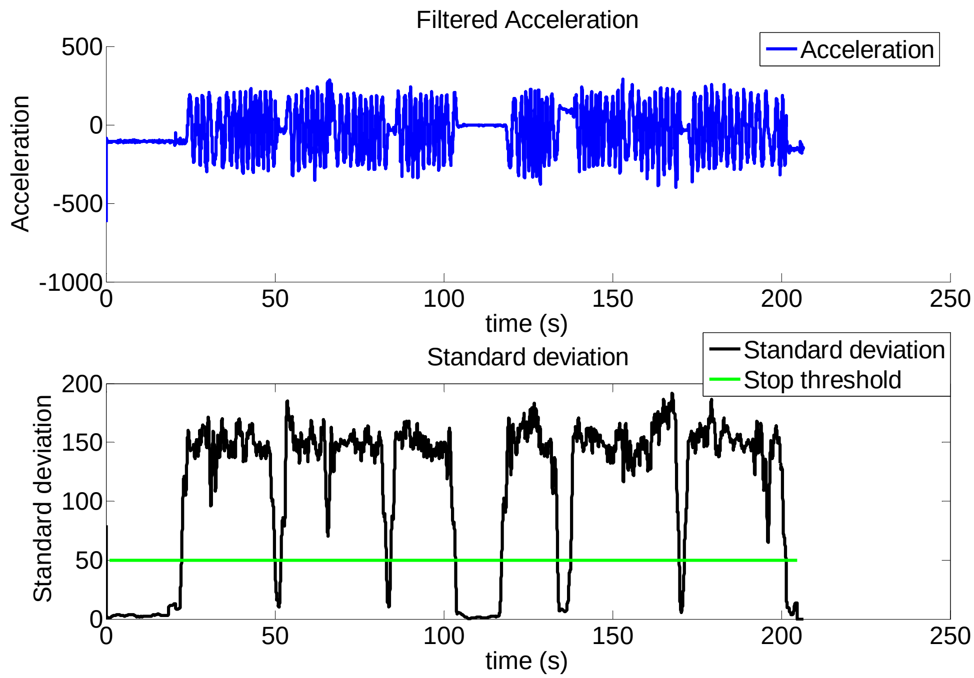



**Figure 73: Outdoor testing acceleration profile and standard deviation subject 3 - right wheel**

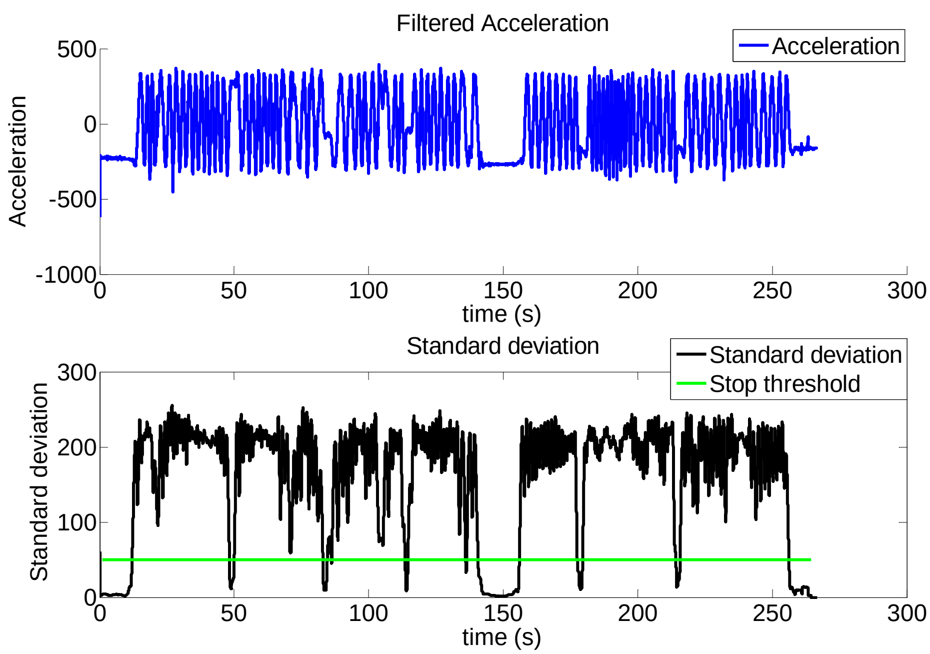



**Figure 74: Outdoor testing acceleration profile and standard deviation subject 4 - right wheel**

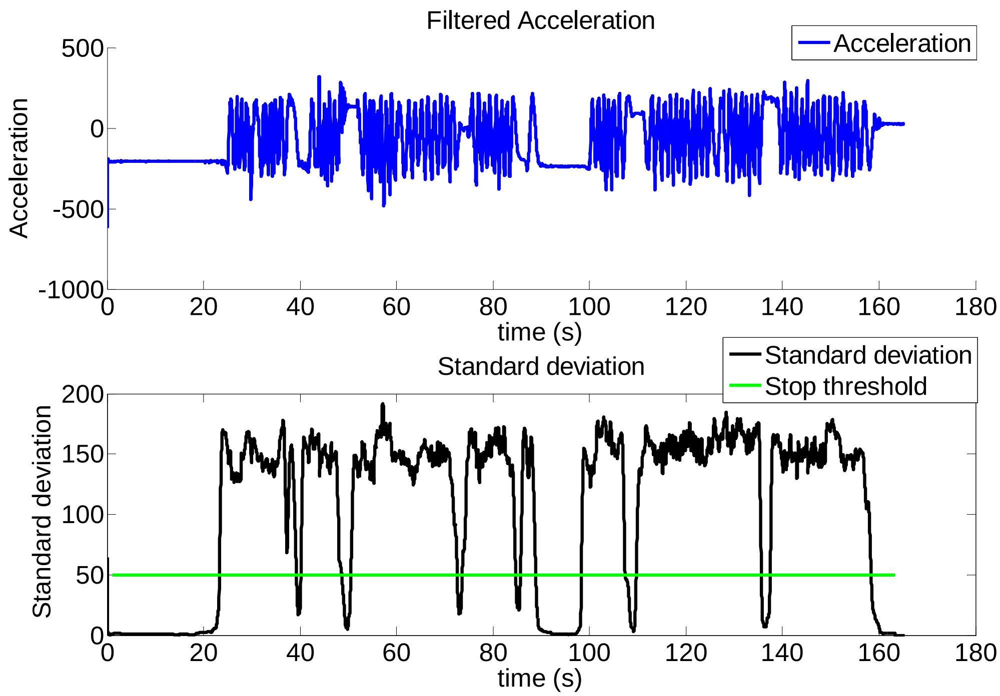



**Figure 75: Outdoor testing acceleration profile and standard deviation subject 5 - right wheel**

# APPENDIX K

# EVERYDAY USAGE BOUTS OF MOBILITY

**Table 41: Self reported bouts subject 1**

| | Break-up of the day as reported by the user | Reported time |
|---|---|---|
| 1 | Lab – Home ( then around the house) | 12:00 |
| 2 | Home - Campus | ≈ 14:45 |
| 3 | Campus – Home (then around the house) | 16:30 – 18:00 |
| 4 | Stop using | 18:00-20:00 |
| 5 | Around the house | 20:00-12:30 |
| 6 | Wake up | 6:30 |
| 7 | Leave for class | 7:45 |

**Table 42: Subject 1 bouts**

| Dist (feet) | M. time (s) | M. Time (mins) | stop time (mins) | Act. Time |
|---|---|---|---|---|
| 119.38 | 43.47 | 0.72 | | 10:23:30 |
| 221.48 | 58.35 | 0.97 | 0.13 | 10:24:21 |
| 1.57 | 2.22 | 0.04 | 1.40 | 10:26:44 |
| 1.57 | 3.47 | 0.06 | 0.03 | 10:26:48 |
| 1.57 | 2.20 | 0.04 | 33.34 | 11:00:11 |
| 1.57 | 2.30 | 0.04 | 1.11 | 11:01:20 |
| 1.57 | 2.00 | 0.03 | 10.92 | 11:12:17 |
| 1.57 | 2.20 | 0.04 | 1.00 | 11:13:19 |
| 1.57 | 3.77 | 0.06 | 7.29 | 11:20:39 |
| 1.57 | 0.98 | 0.02 | 0.35 | 11:21:04 |
| 3.14 | 2.97 | 0.05 | 13.35 | 11:34:26 |
| 15.71 | 11.58 | 0.19 | 24.76 | 11:59:15 |
| 14.14 | 7.02 | 0.12 | 0.29 | 11:59:44 |
| 1753.01 | 393.52 | 6.56 | 0.04 | 11:59:53 |
| 17.28 | 11.43 | 0.19 | 0.10 | 12:06:33 |
| 4.71 | 4.00 | 0.07 | 0.00 | 12:06:45 |
| 25.13 | 17.07 | 0.28 | 0.29 | 12:07:06 |

**Table 42 (Continued)**

| Dist (feet) | M. time (s) | M. Time (mins) | stop time (mins) | Act. Time |
|---|---|---|---|---|
| 21.99 | 15.15 | 0.25 | 0.16 | 12:07:32 |
| 3.14 | 4.00 | 0.07 | 0.18 | 12:07:58 |
| 1.57 | 3.73 | 0.06 | 0.02 | 12:08:03 |
| 7.85 | 11.77 | 0.20 | 0.00 | 12:08:07 |
| 1.57 | 2.43 | 0.04 | 0.02 | 12:08:20 |
| 1.57 | 2.75 | 0.05 | 0.06 | 12:08:26 |
| 1.57 | 2.40 | 0.04 | 56.78 | 13:05:16 |
| 31.42 | 17.17 | 0.29 | 0.01 | 13:05:18 |
| 28.27 | 14.35 | 0.24 | 8.58 | 13:14:11 |
| 4.71 | 4.20 | 0.07 | 0.73 | 13:15:09 |
| 3.14 | 3.35 | 0.06 | 0.11 | 13:15:19 |
| 1.57 | 1.95 | 0.03 | 2.11 | 13:17:29 |
| 17.28 | 10.55 | 0.18 | 0.17 | 13:17:42 |
| 14.14 | 8.18 | 0.14 | 0.15 | 13:18:01 |
| 15.71 | 11.97 | 0.20 | 0.13 | 13:18:17 |
| 14.14 | 8.38 | 0.14 | 0.06 | 13:18:33 |
| 1.57 | 2.45 | 0.04 | 0.01 | 13:18:42 |
| 1.57 | 2.23 | 0.04 | 0.07 | 13:18:48 |
| 3.14 | 3.07 | 0.05 | 0.26 | 13:19:06 |
| 3.14 | 5.37 | 0.09 | 0.21 | 13:19:22 |
| 6.28 | 7.17 | 0.12 | 3.03 | 13:22:29 |
| 6.28 | 5.10 | 0.09 | 1.10 | 13:23:42 |
| 1.57 | 2.17 | 0.04 | 20.80 | 13:44:35 |
| 12.57 | 13.28 | 0.22 | 0.98 | 13:45:36 |
| 1.57 | 2.27 | 0.04 | 0.03 | 13:45:52 |
| 1.57 | 1.80 | 0.03 | 0.20 | 13:46:06 |
| 14.14 | 8.82 | 0.15 | 1.36 | 13:47:29 |
| 1.57 | 2.47 | 0.04 | 0.01 | 13:47:38 |
| 9.42 | 7.00 | 0.12 | 0.04 | 13:47:43 |
| 3.14 | 3.68 | 0.06 | 0.04 | 13:47:52 |
| 1.57 | 1.87 | 0.03 | 1.92 | 13:49:51 |
| 3.14 | 4.63 | 0.08 | 1.06 | 13:50:57 |
| 36.13 | 20.62 | 0.34 | 6.10 | 13:57:07 |
| 4.71 | 3.70 | 0.06 | 0.10 | 13:57:33 |
| 3.14 | 4.83 | 0.08 | 0.01 | 13:57:38 |
| 9.42 | 5.80 | 0.10 | 0.18 | 13:57:54 |
| 1.57 | 2.18 | 0.04 | 0.49 | 13:58:29 |
| 1.57 | 4.82 | 0.08 | 0.01 | 13:58:32 |
| 21.99 | 14.57 | 0.24 | 16.28 | 14:14:53 |
| 3.14 | 2.87 | 0.05 | 0.04 | 14:15:10 |
| 31.42 | 14.17 | 0.24 | 17.44 | 14:32:39 |
| 1.57 | 2.52 | 0.04 | 0.01 | 14:32:54 |

**Table 42 (Continued)**

| Dist (feet) | M. time (s) | M. Time (mins) | stop time (mins) | Act. Time |
|---|---|---|---|---|
| 1.57 | 4.97 | 0.08 | 4.84 | 14:37:47 |
| 26.70 | 13.75 | 0.23 | 0.25 | 14:38:07 |
| 4.71 | 4.40 | 0.07 | 0.12 | 14:38:28 |
| 6.28 | 4.10 | 0.07 | 1.87 | 14:40:25 |
| 3.14 | 3.18 | 0.05 | 0.43 | 14:40:55 |
| 3.14 | 4.62 | 0.08 | 0.48 | 14:41:27 |
| 4.71 | 7.95 | 0.13 | 0.32 | 14:41:51 |
| 14.14 | 6.68 | 0.11 | 0.11 | 14:42:06 |
| 9.42 | 6.05 | 0.10 | 1.17 | 14:43:23 |
| 21.99 | 11.77 | 0.20 | 0.01 | 14:43:29 |
| 1512.68 | 246.18 | 4.10 | 0.02 | 14:43:42 |
| 2670.35 | 402.32 | 6.71 | 0.69 | 14:48:30 |
| 307.88 | 70.32 | 1.17 | 0.02 | 14:55:13 |
| 14.14 | 10.13 | 0.17 | 0.02 | 14:56:25 |
| 2305.93 | 388.28 | 6.47 | 89.43 | 16:26:01 |
| 1.57 | 2.10 | 0.04 | 0.12 | 16:32:36 |
| 2883.98 | 446.58 | 7.44 | 0.02 | 16:32:39 |
| 14.14 | 9.07 | 0.15 | 0.02 | 16:40:07 |
| 25.13 | 12.57 | 0.21 | 0.14 | 16:40:24 |
| 4.71 | 6.48 | 0.11 | 0.44 | 16:41:03 |
| 4.71 | 4.13 | 0.07 | 0.07 | 16:41:14 |
| 42.41 | 18.28 | 0.30 | 5.80 | 16:47:06 |
| 1.57 | 2.17 | 0.04 | 0.02 | 16:47:25 |
| 6.28 | 4.47 | 0.07 | 0.00 | 16:47:28 |
| 6.28 | 5.83 | 0.10 | 0.00 | 16:47:33 |
| 1.57 | 2.42 | 0.04 | 0.23 | 16:47:52 |
| 1.57 | 1.82 | 0.03 | 0.04 | 16:47:57 |
| 1.57 | 1.50 | 0.03 | 1.29 | 16:49:16 |
| 54.98 | 27.27 | 0.45 | 0.01 | 16:49:19 |
| 40.84 | 22.90 | 0.38 | 13.82 | 17:03:35 |
| 28.27 | 14.17 | 0.24 | 3.81 | 17:07:46 |
| 9.42 | 6.15 | 0.10 | 3.83 | 17:11:50 |
| 7.85 | 6.50 | 0.11 | 0.03 | 17:11:58 |
| 1.57 | 2.47 | 0.04 | 3.43 | 17:15:30 |
| 28.27 | 13.60 | 0.23 | 0.02 | 17:15:34 |
| 14.14 | 14.68 | 0.24 | 0.01 | 17:15:48 |
| 1.57 | 2.75 | 0.05 | 0.13 | 17:16:10 |
| 3.14 | 4.65 | 0.08 | 0.35 | 17:16:34 |
| 1.57 | 2.00 | 0.03 | 0.03 | 17:16:41 |
| 11.00 | 10.62 | 0.18 | 6.04 | 17:22:45 |
| 34.56 | 15.38 | 0.26 | 0.68 | 17:23:36 |
| 1.57 | 3.73 | 0.06 | 0.22 | 17:24:05 |

**Table 42 (Continued)**

| Dist (feet) | M. time (s) | M. Time (mins) | stop time (mins) | Act. Time |
|---|---|---|---|---|
| 6.28 | 4.53 | 0.08 | 2.80 | 17:26:56 |
| 1.57 | 2.27 | 0.04 | 0.19 | 17:27:12 |
| 1.57 | 2.15 | 0.04 | 0.00 | 17:27:15 |
| 18.85 | 12.35 | 0.21 | 7.05 | 17:34:20 |
| 3.14 | 3.77 | 0.06 | 0.01 | 17:34:33 |
| 12.57 | 8.73 | 0.15 | 0.04 | 17:34:39 |
| 21.99 | 13.30 | 0.22 | 0.47 | 17:35:16 |
| 3.14 | 4.35 | 0.07 | 0.04 | 17:35:31 |
| 25.13 | 12.22 | 0.20 | 0.13 | 17:35:44 |
| 3.14 | 3.53 | 0.06 | 0.61 | 17:36:33 |
| 15.71 | 12.93 | 0.22 | 0.01 | 17:36:36 |
| 9.42 | 7.37 | 0.12 | 0.11 | 17:36:56 |
| 1.57 | 2.17 | 0.04 | 0.29 | 17:37:21 |
| 11.00 | 7.20 | 0.12 | 0.00 | 17:37:23 |
| 15.71 | 10.52 | 0.18 | 0.05 | 17:37:33 |
| 1.57 | 2.25 | 0.04 | 0.04 | 17:37:46 |
| 20.42 | 11.47 | 0.19 | 0.04 | 17:37:51 |
| 3.14 | 2.93 | 0.05 | 1.36 | 17:39:24 |
| 1.57 | 1.95 | 0.03 | 8.41 | 17:47:51 |
| 11.00 | 7.08 | 0.12 | 15.45 | 18:03:20 |
| 1.57 | 2.00 | 0.03 | 0.03 | 18:03:29 |
| 3.14 | 3.97 | 0.07 | 0.02 | 18:03:32 |
| 3.14 | 3.02 | 0.05 | 0.00 | 18:03:36 |
| 53.41 | 33.25 | 0.55 | 0.36 | 18:04:01 |
| 1.57 | 2.10 | 0.04 | 4.04 | 18:08:36 |
| 28.27 | 15.45 | 0.26 | 0.79 | 18:09:25 |
| 1.57 | 3.95 | 0.07 | 0.34 | 18:10:01 |
| 1.57 | 3.00 | 0.05 | 0.05 | 18:10:08 |
| 1.57 | 2.10 | 0.04 | 0.07 | 18:10:15 |
| 3.14 | 3.20 | 0.05 | 0.10 | 18:10:23 |
| 7.85 | 6.40 | 0.11 | 0.41 | 18:10:51 |
| 7.85 | 6.10 | 0.10 | 0.01 | 18:10:58 |
| 7.85 | 5.57 | 0.09 | 0.31 | 18:11:22 |
| 6.28 | 6.37 | 0.11 | 0.19 | 18:11:39 |
| 1.57 | 2.17 | 0.04 | 0.20 | 18:11:57 |
| 1.57 | 2.45 | 0.04 | 0.02 | 18:12:01 |
| 37.70 | 25.35 | 0.42 | 1.02 | 18:13:05 |
| 3.14 | 3.30 | 0.06 | 3.16 | 18:16:39 |
| 6.28 | 6.42 | 0.11 | 265.09 | 22:41:48 |
| 3.14 | 3.55 | 0.06 | 0.07 | 22:41:59 |
| 3.14 | 4.38 | 0.07 | 2.01 | 22:44:03 |
| 3.14 | 3.53 | 0.06 | 0.11 | 22:44:14 |

**Table 42 (Continued)**

| Dist (feet) | M. time (s) | M. Time (mins) | stop time (mins) | Act. Time |
|---|---|---|---|---|
| 1.57 | 2.77 | 0.05 | 4.34 | 22:48:38 |
| 1.57 | 2.15 | 0.04 | 0.09 | 22:48:46 |
| 32.99 | 17.27 | 0.29 | 20.35 | 23:09:09 |
| 14.14 | 10.70 | 0.18 | 0.35 | 23:09:47 |
| 15.71 | 8.93 | 0.15 | 0.04 | 23:10:00 |
| 31.42 | 15.48 | 0.26 | 70.00 | 0:20:08 |
| 1.57 | 3.13 | 0.05 | 0.03 | 0:20:25 |
| 1.57 | 2.27 | 0.04 | 0.25 | 0:20:43 |
| 28.27 | 14.83 | 0.25 | 6.36 | 0:27:07 |
| 59.69 | 35.68 | 0.59 | 0.02 | 0:27:23 |
| 34.56 | 18.47 | 0.31 | 4.18 | 0:32:10 |
| 23.56 | 13.18 | 0.22 | 2.83 | 0:35:18 |
| 29.85 | 13.47 | 0.22 | 396.04 | 7:11:34 |
| 1.57 | 2.25 | 0.04 | 0.26 | 7:12:03 |
| 1.57 | 2.17 | 0.04 | 2.24 | 7:14:20 |
| 3.14 | 3.43 | 0.06 | 14.78 | 7:29:09 |
| 6.28 | 6.75 | 0.11 | 1.33 | 7:30:32 |
| 21.99 | 13.03 | 0.22 | 13.75 | 7:44:24 |
| 4.71 | 5.85 | 0.10 | 1.87 | 7:46:29 |
| 1.57 | 0.80 | 0.01 | 0.07 | 7:46:40 |
| 1.57 | 3.33 | 0.06 | 0.97 | 7:47:39 |
| 1.57 | 2.58 | 0.04 | 0.25 | 7:47:57 |
| 12.57 | 7.15 | 0.12 | 0.10 | 7:48:06 |
| 3.14 | 3.40 | 0.06 | 0.12 | 7:48:21 |
| 1.57 | 3.52 | 0.06 | 0.02 | 7:48:25 |
| 282.74 | 71.55 | 1.19 | 0.00 | 7:48:29 |
| 1229.93 | 281.60 | 4.69 | 0.03 | 7:49:42 |
| 3103.89 | 488.72 | 8.15 | 0.87 | 7:55:15 |
| 1.57 | 1.62 | 0.03 | 1.39 | 8:04:48 |
| 1460.84 | 282.12 | 4.70 | 50.90 | 8:55:43 |
| 1.57 | 0.77 | 0.01 | 0.03 | 9:00:27 |
| 9.42 | 6.92 | 0.12 | 0.01 | 9:00:29 |
| 91.11 | 28.88 | 0.48 | 0.01 | 9:00:36 |
| | | | | |
| **Total dist.(miles)** | | **Total time (mins)** | | |
| **3.71** | | **72.41** | | |

**Table 43: Self reported bouts Subject 2**

| | Break-up of the day as reported by the user | Reported time |
|---|---|---|
| 1 | Lab – Martha station | 16:00 |
| 2 | Martha ride | ≈ 40 mins |
| 3 | Wal-Mart | 17:45 – 18:30 |
| 4 | Home | Till 20:00 |
| 5 | Wake up around | 7:00 |
| 6 | Get to work | ≈ 9:30 |
| 7 | Across campus then lunch at tech square | 11:00 – 13:00 |

**Table 44: Subject 2 bouts**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 1.57 | 2.62 | 0.04 | | 15:25:51 |
| 285.88 | 81.83 | 1.36 | 0.61 | 15:26:30 |
| 73.83 | 24.52 | 0.41 | 0.22 | 15:28:04 |
| 1.57 | 3.45 | 0.06 | 0.05 | 15:28:32 |
| 17.28 | 9.03 | 0.15 | 0.04 | 15:28:38 |
| 9.42 | 5.17 | 0.09 | 1.86 | 15:30:38 |
| 1.57 | 1.98 | 0.03 | 0.20 | 15:30:56 |
| 58.12 | 23.97 | 0.40 | 0.02 | 15:30:59 |
| 7.85 | 6.88 | 0.11 | 0.00 | 15:31:23 |
| 1.57 | 2.17 | 0.04 | 0.00 | 15:31:30 |
| 1.57 | 1.97 | 0.03 | 0.11 | 15:31:39 |
| 1.57 | 1.98 | 0.03 | 4.19 | 15:35:53 |
| 3.14 | 2.82 | 0.05 | 0.06 | 15:35:58 |
| 1.57 | 2.02 | 0.03 | 1.23 | 15:37:14 |
| 1.57 | 1.98 | 0.03 | 0.07 | 15:37:21 |
| 1.57 | 1.77 | 0.03 | 0.17 | 15:37:33 |
| 1.57 | 2.15 | 0.04 | 0.02 | 15:37:36 |
| 1.57 | 2.40 | 0.04 | 0.02 | 15:37:39 |
| 1.57 | 1.72 | 0.03 | 0.09 | 15:37:47 |
| 1.57 | 2.23 | 0.04 | 0.01 | 15:37:49 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 6.28 | 4.13 | 0.07 | 0.97 | 15:38:49 |
| 12.57 | 10.58 | 0.18 | 0.01 | 15:38:54 |
| 3.14 | 4.33 | 0.07 | 0.01 | 15:39:05 |
| 11.00 | 8.25 | 0.14 | 2.08 | 15:41:15 |
| 65.97 | 27.77 | 0.46 | 0.70 | 15:42:05 |
| 3.14 | 4.42 | 0.07 | 0.28 | 15:42:49 |
| 1.57 | 2.10 | 0.04 | 0.34 | 15:43:14 |
| 1.57 | 1.82 | 0.03 | 0.06 | 15:43:20 |
| 6.28 | 5.23 | 0.09 | 0.01 | 15:43:22 |
| 6.28 | 4.12 | 0.07 | 0.48 | 15:43:57 |
| 4.71 | 4.58 | 0.08 | 0.01 | 15:44:01 |
| 1.57 | 2.70 | 0.05 | 0.24 | 15:44:20 |
| 11.00 | 10.60 | 0.18 | 0.09 | 15:44:28 |
| 11.00 | 8.58 | 0.14 | 0.01 | 15:44:40 |
| 4.71 | 5.62 | 0.09 | 1.07 | 15:45:52 |
| 6.28 | 7.45 | 0.12 | 0.32 | 15:46:17 |
| 1.57 | 1.88 | 0.03 | 4.31 | 15:50:44 |
| 29.85 | 16.97 | 0.28 | 0.04 | 15:50:48 |
| 80.11 | 30.02 | 0.50 | 0.17 | 15:51:15 |
| 1.57 | 3.75 | 0.06 | 0.61 | 15:52:22 |
| 1.57 | 1.18 | 0.02 | 2.51 | 15:54:56 |
| 4.71 | 6.97 | 0.12 | 1.06 | 15:56:00 |
| 3.14 | 3.32 | 0.06 | 0.73 | 15:56:51 |
| 1.57 | 1.78 | 0.03 | 1.15 | 15:58:03 |
| 3.14 | 2.93 | 0.05 | 0.85 | 15:58:56 |
| 23.56 | 11.40 | 0.19 | 0.01 | 15:59:00 |
| 20.42 | 8.75 | 0.15 | 0.06 | 15:59:14 |
| 4531.75 | 616.53 | 10.28 | 0.06 | 15:59:27 |
| 1022.59 | 151.88 | 2.53 | 0.00 | 16:09:44 |
| 1.57 | 2.93 | 0.05 | 0.70 | 16:12:57 |
| 3.14 | 3.18 | 0.05 | 0.00 | 16:13:00 |
| 9.42 | 9.05 | 0.15 | 0.01 | 16:13:04 |
| 12.57 | 8.48 | 0.14 | 0.22 | 16:13:27 |
| 1.57 | 2.08 | 0.03 | 0.02 | 16:13:36 |
| 14.14 | 7.90 | 0.13 | 0.05 | 16:13:41 |
| 3.14 | 3.42 | 0.06 | 5.21 | 16:19:02 |
| 1.57 | 2.25 | 0.04 | 0.09 | 16:19:10 |
| 1.57 | 2.53 | 0.04 | 0.00 | 16:19:13 |
| 3.14 | 6.30 | 0.11 | 0.03 | 16:19:17 |
| 3.14 | 3.52 | 0.06 | 0.05 | 16:19:27 |
| 1.57 | 2.73 | 0.05 | 0.03 | 16:19:32 |
| 1.57 | 2.43 | 0.04 | 0.00 | 16:19:35 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 3.14 | 3.42 | 0.06 | 0.11 | 16:19:44 |
| 1.57 | 2.62 | 0.04 | 0.03 | 16:19:49 |
| 1.57 | 3.05 | 0.05 | 0.01 | 16:19:52 |
| 1.57 | 2.93 | 0.05 | 0.04 | 16:19:58 |
| 1.57 | 3.57 | 0.06 | 0.03 | 16:20:02 |
| 1.57 | 4.45 | 0.07 | 0.10 | 16:20:12 |
| 1.57 | 1.37 | 0.02 | 0.12 | 16:20:23 |
| 1.57 | 2.23 | 0.04 | 0.02 | 16:20:26 |
| 1.57 | 2.10 | 0.04 | 0.03 | 16:20:30 |
| 1.57 | 2.57 | 0.04 | 0.01 | 16:20:32 |
| 14.14 | 9.67 | 0.16 | 6.46 | 16:27:03 |
| 3.14 | 3.23 | 0.05 | 0.02 | 16:27:14 |
| 3.14 | 4.67 | 0.08 | 0.02 | 16:27:18 |
| 6.28 | 5.92 | 0.10 | 0.00 | 16:27:23 |
| 12.57 | 9.60 | 0.16 | 0.45 | 16:27:56 |
| 1.57 | 3.27 | 0.05 | 0.04 | 16:28:08 |
| 1.57 | 2.58 | 0.04 | 0.01 | 16:28:12 |
| 18.85 | 21.38 | 0.36 | 0.16 | 16:28:24 |
| 3.14 | 2.77 | 0.05 | 45.85 | 17:14:36 |
| 1.57 | 3.48 | 0.06 | 0.02 | 17:14:40 |
| 72.26 | 28.17 | 0.47 | 0.09 | 17:14:49 |
| 3.14 | 4.72 | 0.08 | 0.38 | 17:15:40 |
| 9.42 | 7.63 | 0.13 | 0.03 | 17:15:46 |
| 1.57 | 1.73 | 0.03 | 0.05 | 17:15:57 |
| 3.14 | 3.72 | 0.06 | 37.00 | 17:52:59 |
| 12.57 | 8.72 | 0.15 | 0.02 | 17:53:04 |
| 163.36 | 45.62 | 0.76 | 0.21 | 17:53:25 |
| 73.83 | 27.97 | 0.47 | 0.03 | 17:54:12 |
| 31.42 | 21.93 | 0.37 | 0.02 | 17:54:41 |
| 12.57 | 9.32 | 0.16 | 0.04 | 17:55:06 |
| 7.85 | 6.95 | 0.12 | 0.02 | 17:55:16 |
| 224.62 | 62.08 | 1.03 | 0.02 | 17:55:24 |
| 11.00 | 7.80 | 0.13 | 0.23 | 17:56:40 |
| 31.42 | 14.60 | 0.24 | 0.31 | 17:57:07 |
| 31.42 | 14.57 | 0.24 | 0.01 | 17:57:22 |
| 1.57 | 1.92 | 0.03 | 0.01 | 17:57:37 |
| 1.57 | 2.00 | 0.03 | 0.01 | 17:57:40 |
| 1.57 | 2.02 | 0.03 | 0.10 | 17:57:47 |
| 1.57 | 2.82 | 0.05 | 0.25 | 17:58:04 |
| 728.85 | 208.58 | 3.48 | 0.18 | 17:58:18 |
| 131.95 | 64.30 | 1.07 | 0.06 | 18:01:50 |
| 141.37 | 77.83 | 1.30 | 0.01 | 18:02:55 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 29.85 | 22.65 | 0.38 | 0.06 | 18:04:16 |
| 1.57 | 2.17 | 0.04 | 0.01 | 18:04:40 |
| 3.14 | 5.60 | 0.09 | 0.04 | 18:04:44 |
| 18.85 | 17.35 | 0.29 | 0.02 | 18:04:51 |
| 1.57 | 2.97 | 0.05 | 0.02 | 18:05:10 |
| 1.57 | 2.83 | 0.05 | 0.02 | 18:05:14 |
| 3.14 | 4.48 | 0.07 | 0.01 | 18:05:17 |
| 1.57 | 4.75 | 0.08 | 0.01 | 18:05:22 |
| 1.57 | 1.67 | 0.03 | 0.01 | 18:05:28 |
| 1.57 | 2.83 | 0.05 | 0.07 | 18:05:33 |
| 1.57 | 2.25 | 0.04 | 0.02 | 18:05:37 |
| 17.28 | 14.57 | 0.24 | 0.03 | 18:05:41 |
| 20.42 | 19.90 | 0.33 | 0.06 | 18:05:59 |
| 124.09 | 60.72 | 1.01 | 0.10 | 18:06:25 |
| 174.36 | 60.23 | 1.00 | 0.00 | 18:07:26 |
| 12.57 | 10.22 | 0.17 | 0.03 | 18:08:28 |
| 1.57 | 2.27 | 0.04 | 0.03 | 18:08:40 |
| 1.57 | 2.70 | 0.05 | 0.00 | 18:08:43 |
| 14.14 | 14.42 | 0.24 | 0.02 | 18:08:46 |
| 1.57 | 2.40 | 0.04 | 0.01 | 18:09:01 |
| 1.57 | 1.98 | 0.03 | 0.32 | 18:09:23 |
| 166.50 | 48.25 | 0.80 | 0.01 | 18:09:26 |
| 6.28 | 7.33 | 0.12 | 0.05 | 18:10:17 |
| 15.71 | 13.45 | 0.22 | 0.05 | 18:10:27 |
| 4.71 | 4.42 | 0.07 | 8.57 | 18:19:15 |
| 51.84 | 19.90 | 0.33 | 0.01 | 18:19:19 |
| 39.27 | 17.22 | 0.29 | 0.70 | 18:20:21 |
| 1.57 | 1.85 | 0.03 | 0.12 | 18:20:45 |
| 4.71 | 5.38 | 0.09 | 0.31 | 18:21:06 |
| 3.14 | 5.07 | 0.08 | 0.01 | 18:21:12 |
| 11.00 | 10.80 | 0.18 | 41.92 | 19:03:12 |
| 72.26 | 30.57 | 0.51 | 0.28 | 19:03:40 |
| 1.57 | 2.30 | 0.04 | 0.01 | 19:04:11 |
| 58.12 | 25.15 | 0.42 | 0.26 | 19:04:29 |
| 15.71 | 10.82 | 0.18 | 0.01 | 19:04:54 |
| 1.57 | 1.87 | 0.03 | 63.95 | 20:09:02 |
| 3.14 | 4.82 | 0.08 | 0.08 | 20:09:09 |
| 11.00 | 9.52 | 0.16 | 0.02 | 20:09:15 |
| 9.42 | 9.08 | 0.15 | 0.09 | 20:09:30 |
| 64.40 | 23.42 | 0.39 | 0.29 | 20:09:56 |
| 12.57 | 9.67 | 0.16 | 0.85 | 20:11:10 |
| 1.57 | 3.15 | 0.05 | 669.62 | 7:20:57 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 1.57 | 2.18 | 0.04 | 0.08 | 7:21:05 |
| 47.12 | 22.72 | 0.38 | 0.14 | 7:21:15 |
| 12.57 | 12.30 | 0.21 | 0.01 | 7:21:39 |
| 1.57 | 2.65 | 0.04 | 0.58 | 7:22:26 |
| 1.57 | 3.90 | 0.07 | 0.50 | 7:22:59 |
| 1.57 | 2.97 | 0.05 | 31.48 | 7:54:31 |
| 1.57 | 2.07 | 0.03 | 0.28 | 7:54:51 |
| 11.00 | 6.30 | 0.11 | 0.00 | 7:54:54 |
| 84.82 | 22.70 | 0.38 | 0.33 | 7:55:20 |
| 4.71 | 4.17 | 0.07 | 0.10 | 7:55:48 |
| 12.57 | 9.33 | 0.16 | 0.01 | 7:55:53 |
| 21.99 | 13.98 | 0.23 | 55.94 | 8:51:59 |
| 1.57 | 2.22 | 0.04 | 0.03 | 8:52:14 |
| 1.57 | 2.32 | 0.04 | 0.30 | 8:52:35 |
| 83.25 | 16.48 | 0.27 | 0.03 | 8:52:39 |
| 1366.59 | 193.40 | 3.22 | 0.11 | 8:53:02 |
| 1.57 | 2.60 | 0.04 | 0.21 | 8:56:28 |
| 427.26 | 61.90 | 1.03 | 0.13 | 8:56:39 |
| 1072.85 | 155.20 | 2.59 | 0.01 | 8:57:41 |
| 1209.51 | 181.58 | 3.03 | 0.04 | 9:00:19 |
| 1.57 | 1.95 | 0.03 | 0.02 | 9:03:22 |
| 797.96 | 119.68 | 1.99 | 0.12 | 9:03:31 |
| 578.05 | 85.57 | 1.43 | 0.04 | 9:05:33 |
| 78.54 | 27.08 | 0.45 | 0.04 | 9:07:01 |
| 1.57 | 3.55 | 0.06 | 0.63 | 9:08:06 |
| 1.57 | 2.10 | 0.04 | 0.04 | 9:08:12 |
| 3.14 | 3.20 | 0.05 | 0.27 | 9:08:30 |
| 15.71 | 11.98 | 0.20 | 0.21 | 9:08:46 |
| 1.57 | 2.50 | 0.04 | 0.71 | 9:09:40 |
| 43.98 | 20.48 | 0.34 | 29.68 | 9:39:23 |
| 54.98 | 22.52 | 0.38 | 0.94 | 9:40:40 |
| 1.57 | 2.70 | 0.05 | 13.66 | 9:54:42 |
| 1.57 | 2.95 | 0.05 | 0.02 | 9:54:46 |
| 89.54 | 35.72 | 0.60 | 0.24 | 9:55:03 |
| 21.99 | 11.25 | 0.19 | 0.10 | 9:55:45 |
| 75.40 | 34.60 | 0.58 | 37.42 | 10:33:21 |
| 64.40 | 28.22 | 0.47 | 0.17 | 10:34:06 |
| 1.57 | 1.50 | 0.03 | 0.10 | 10:34:41 |
| 6.28 | 5.88 | 0.10 | 0.13 | 10:34:50 |
| 6.28 | 3.63 | 0.06 | 0.07 | 10:35:00 |
| 1.57 | 2.65 | 0.04 | 0.01 | 10:35:05 |
| 4.71 | 5.47 | 0.09 | 0.01 | 10:35:08 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 9.42 | 6.58 | 0.11 | 0.09 | 10:35:19 |
| 1.57 | 1.88 | 0.03 | 29.63 | 11:05:04 |
| 1.57 | 1.42 | 0.02 | 0.00 | 11:05:06 |
| 1.57 | 2.17 | 0.04 | 0.09 | 11:05:12 |
| 1.57 | 2.10 | 0.04 | 0.06 | 11:05:18 |
| 1.57 | 2.15 | 0.04 | 0.30 | 11:05:38 |
| 3.14 | 3.45 | 0.06 | 0.01 | 11:05:41 |
| 1.57 | 2.10 | 0.04 | 0.01 | 11:05:45 |
| 7.85 | 6.92 | 0.12 | 0.81 | 11:06:36 |
| 62.83 | 20.88 | 0.35 | 0.22 | 11:06:56 |
| 11.00 | 6.87 | 0.11 | 0.00 | 11:07:17 |
| 17.28 | 8.75 | 0.15 | 0.00 | 11:07:24 |
| 1390.15 | 196.40 | 3.27 | 0.02 | 11:07:34 |
| 3564.14 | 500.03 | 8.33 | 0.04 | 11:10:53 |
| 1.57 | 3.87 | 0.06 | 0.37 | 11:19:35 |
| 764.98 | 107.60 | 1.79 | 0.26 | 11:19:55 |
| 1525.24 | 222.83 | 3.71 | 0.40 | 11:22:06 |
| 1.57 | 2.13 | 0.04 | 0.02 | 11:25:50 |
| 11.00 | 5.10 | 0.09 | 0.23 | 11:26:06 |
| 62.83 | 18.95 | 0.32 | 0.36 | 11:26:33 |
| 1.57 | 2.17 | 0.04 | 0.01 | 11:26:53 |
| 100.53 | 26.57 | 0.44 | 0.28 | 11:27:12 |
| 12.57 | 6.23 | 0.10 | 0.26 | 11:27:54 |
| 32.99 | 16.70 | 0.28 | 0.38 | 11:28:23 |
| 4.71 | 3.45 | 0.06 | 0.60 | 11:29:16 |
| 1.57 | 2.33 | 0.04 | 0.01 | 11:29:20 |
| 1.57 | 2.53 | 0.04 | 0.01 | 11:29:23 |
| 21.99 | 15.72 | 0.26 | 0.06 | 11:29:29 |
| 1.57 | 2.32 | 0.04 | 0.00 | 11:29:45 |
| 56.55 | 25.67 | 0.43 | 1.45 | 11:31:14 |
| 4.71 | 4.73 | 0.08 | 3.94 | 11:35:36 |
| 271.75 | 66.77 | 1.11 | 0.20 | 11:35:53 |
| 1.57 | 2.05 | 0.03 | 0.99 | 11:37:59 |
| 1.57 | 2.00 | 0.03 | 0.05 | 11:38:04 |
| 11.00 | 8.53 | 0.14 | 0.03 | 11:38:08 |
| 175.93 | 44.43 | 0.74 | 0.50 | 11:38:46 |
| 116.24 | 30.67 | 0.51 | 0.01 | 11:39:32 |
| 1672.90 | 279.57 | 4.66 | 0.02 | 11:40:03 |
| 1.57 | 2.53 | 0.04 | 0.20 | 11:44:55 |
| 1.57 | 2.10 | 0.04 | 0.00 | 11:44:58 |
| 43.98 | 13.03 | 0.22 | 0.02 | 11:45:01 |
| 1.57 | 2.02 | 0.03 | 0.09 | 11:45:19 |

Table 44 (Continued)

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 3.14 | 5.23 | 0.09 | 0.02 | 11:45:22 |
| 15.71 | 9.17 | 0.15 | 1.26 | 11:46:43 |
| 11.00 | 6.25 | 0.10 | 0.38 | 11:47:15 |
| 37.70 | 21.48 | 0.36 | 0.01 | 11:47:22 |
| 1.57 | 2.77 | 0.05 | 0.00 | 11:47:44 |
| 21.99 | 18.25 | 0.30 | 0.23 | 11:48:00 |
| 3.14 | 1.90 | 0.03 | 0.12 | 11:48:26 |
| 11.00 | 9.57 | 0.16 | 0.01 | 11:48:28 |
| 14.14 | 7.40 | 0.12 | 0.01 | 11:48:38 |
| 4.71 | 4.67 | 0.08 | 0.11 | 11:48:53 |
| 23.56 | 10.27 | 0.17 | 0.21 | 11:49:10 |
| 15.71 | 6.97 | 0.12 | 0.05 | 11:49:24 |
| 1.57 | 3.38 | 0.06 | 0.13 | 11:49:38 |
| 1.57 | 2.05 | 0.03 | 0.00 | 11:49:42 |
| 1.57 | 2.83 | 0.05 | 0.01 | 11:49:44 |
| 11.00 | 11.23 | 0.19 | 0.03 | 11:49:48 |
| 317.30 | 91.92 | 1.53 | 0.44 | 11:50:26 |
| 175.93 | 54.45 | 0.91 | 0.01 | 11:51:59 |
| 25.13 | 13.63 | 0.23 | 0.02 | 11:52:54 |
| 1.57 | 2.05 | 0.03 | 0.67 | 11:53:48 |
| 1.57 | 2.05 | 0.03 | 0.78 | 11:54:37 |
| 1.57 | 1.98 | 0.03 | 0.31 | 11:54:58 |
| 1.57 | 2.42 | 0.04 | 1.25 | 11:56:15 |
| 15.71 | 8.33 | 0.14 | 0.01 | 11:56:18 |
| 95.82 | 37.38 | 0.62 | 0.01 | 11:56:27 |
| 1.57 | 2.75 | 0.05 | 21.08 | 12:18:09 |
| 1.57 | 2.22 | 0.04 | 0.07 | 12:18:16 |
| 7.85 | 10.22 | 0.17 | 0.01 | 12:18:19 |
| 75.40 | 37.08 | 0.62 | 0.18 | 12:18:39 |
| 243.47 | 59.88 | 1.00 | 0.02 | 12:19:17 |
| 1482.83 | 258.83 | 4.31 | 0.02 | 12:20:18 |
| 9.42 | 4.65 | 0.08 | 0.33 | 12:24:57 |
| 14.14 | 5.78 | 0.10 | 0.11 | 12:25:08 |
| 20.42 | 7.90 | 0.13 | 0.36 | 12:25:36 |
| 1.57 | 1.85 | 0.03 | 0.80 | 12:26:32 |
| 11.00 | 9.35 | 0.16 | 0.05 | 12:26:36 |
| 72.26 | 20.75 | 0.35 | 0.61 | 12:27:22 |
| 1.57 | 2.12 | 0.04 | 2.01 | 12:29:43 |
| 1.57 | 2.10 | 0.04 | 0.20 | 12:29:57 |
| 14.14 | 9.78 | 0.16 | 0.03 | 12:30:01 |
| 1.57 | 2.55 | 0.04 | 0.01 | 12:30:12 |
| 1.57 | 3.73 | 0.06 | 3.98 | 12:34:13 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 54.98 | 16.55 | 0.28 | 0.47 | 12:34:44 |
| 1.57 | 2.12 | 0.04 | 0.03 | 12:35:03 |
| 3.14 | 5.65 | 0.09 | 0.01 | 12:35:06 |
| 11.00 | 5.97 | 0.10 | 0.14 | 12:35:20 |
| 50.27 | 14.32 | 0.24 | 0.33 | 12:35:45 |
| 138.23 | 37.28 | 0.62 | 0.02 | 12:36:01 |
| 18.85 | 7.40 | 0.12 | 0.04 | 12:36:40 |
| 98.96 | 19.42 | 0.32 | 0.02 | 12:36:49 |
| 837.23 | 122.63 | 2.04 | 0.00 | 12:37:09 |
| 1.57 | 2.02 | 0.03 | 0.16 | 12:39:21 |
| 3.14 | 5.38 | 0.09 | 0.13 | 12:39:30 |
| 3.14 | 3.28 | 0.05 | 0.00 | 12:39:36 |
| 1.57 | 2.52 | 0.04 | 0.11 | 12:39:46 |
| 510.51 | 78.38 | 1.31 | 0.63 | 12:40:26 |
| 1.57 | 2.95 | 0.05 | 0.02 | 12:41:45 |
| 1.57 | 3.12 | 0.05 | 0.23 | 12:42:02 |
| 9.42 | 11.98 | 0.20 | 0.07 | 12:42:09 |
| 3.14 | 4.27 | 0.07 | 0.16 | 12:42:31 |
| 273.32 | 45.42 | 0.76 | 0.00 | 12:42:35 |
| 14.14 | 8.95 | 0.15 | 0.09 | 12:43:26 |
| 3.14 | 3.83 | 0.06 | 0.12 | 12:43:42 |
| 1.57 | 1.88 | 0.03 | 0.01 | 12:43:46 |
| 18.85 | 9.23 | 0.15 | 0.50 | 12:44:18 |
| 1.57 | 2.95 | 0.05 | 0.07 | 12:44:32 |
| 1.57 | 1.77 | 0.03 | 13.52 | 12:58:06 |
| 21.99 | 9.92 | 0.17 | 0.01 | 12:58:08 |
| 26.70 | 13.02 | 0.22 | 1.72 | 13:00:01 |
| 655.02 | 90.90 | 1.52 | 0.09 | 13:00:19 |
| 427.26 | 63.38 | 1.06 | 0.10 | 13:01:56 |
| 1.57 | 3.38 | 0.06 | 0.11 | 13:03:06 |
| 1452.99 | 213.42 | 3.56 | 0.21 | 13:03:22 |
| 4.71 | 4.88 | 0.08 | 0.00 | 13:06:55 |
| 2189.69 | 306.18 | 5.10 | 0.01 | 13:07:01 |
| 108.38 | 43.10 | 0.72 | 0.02 | 13:12:09 |
| 1.57 | 2.90 | 0.05 | 0.49 | 13:13:21 |
| 120.95 | 43.27 | 0.72 | 3.36 | 13:16:46 |
| 131.95 | 51.45 | 0.86 | 0.52 | 13:18:00 |
| 54.98 | 20.70 | 0.35 | 6.44 | 13:25:18 |
| 1.57 | 2.05 | 0.03 | 0.04 | 13:25:41 |
| 43.98 | 23.80 | 0.40 | 0.03 | 13:25:45 |
| 15.71 | 14.53 | 0.24 | 0.37 | 13:26:32 |
| 1.57 | 1.45 | 0.02 | 0.49 | 13:27:16 |

**Table 44 (Continued)**

| Dist(feet) | M. time(s) | M. time(mins) | S. time(mins) | Act. Time hr |
|---|---|---|---|---|
| 62.83 | 21.72 | 0.36 | 0.07 | 13:27:22 |
| 12.57 | 13.00 | 0.22 | 20.11 | 13:47:50 |
| 1.57 | 2.12 | 0.04 | 0.04 | 13:48:05 |
| 4.71 | 5.50 | 0.09 | 0.23 | 13:48:22 |
| 1.57 | 2.07 | 0.03 | 0.00 | 13:48:27 |
| 6.28 | 8.02 | 0.13 | 0.02 | 13:48:30 |
| 1.57 | 2.68 | 0.04 | 0.06 | 13:48:42 |
| 4.71 | 7.15 | 0.12 | 0.00 | 13:48:45 |
| 4.71 | 6.02 | 0.10 | 0.00 | 13:48:52 |
| 1.57 | 2.38 | 0.04 | 0.01 | 13:48:59 |
| 7.85 | 8.55 | 0.14 | 19.45 | 14:08:28 |
| 4.71 | 4.37 | 0.07 | 0.02 | 14:08:38 |
| 51.84 | 24.65 | 0.41 | 0.01 | 14:08:43 |
| 4.71 | 5.12 | 0.09 | 0.01 | 14:09:08 |
| 1.57 | 1.30 | 0.02 | 6.00 | 14:15:13 |
| | | | | |
| **Total Dist. (miles)** | | **Total time (mins)** | | |
| **6.76** | | 125.23 | | |

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